

SAX Observers' Handbook

Issue 1.0

Jul. 7, 1995

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on behalf of the
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1. Introduction

The purpose of this document is to provide the information required to prepare an observation proposal for the SAX X-ray Astronomy Satellite. This document is divided into the following sections:

Section. 2 is a brief summary of the mission. It outlines the overall characteristics of the mission, its scientific objectives and strategy.

Section 3 illustrates the main SAX observational constraints dictated by satellite characteristics such as solar panel alignment and the spacecraft orbit. The regions of the sky accessible to SAX during the year are presented. This chapter is therefore particularly relevant to programs that foresee time critical observations (e.g., co-ordination with other ground or satellite observations, or observations at defined times predicted by source behavior). The SAX Target of Opportunity (TOO) policy is presented.

Section 4 provides information on the performance and characteristics of the SAX instrumentation. This section provides the information required in order to investigate the feasibility of a proposed observation with SAX. In particular, information on how well source characteristics such as flux, spectral shape and variability can be constrained for a particular observation duration using SAX is presented. One of the most important considerations for observing sources brighter than 0.3 Crab with SAX is telemetry allocation. This is because there is insufficient telemetry to use the full direct modes (where each event is transmitted with the full information) for all instruments simultaneously for these sources. In such cases the observer will need to define the subset of information that is required by selecting data transmission modes or instruments most relevant to the scientific goals (e.g temporal vs. imaging vs. energy information). The tools available for simulations (spectral, count rate and bit rate) are also presented in this section.

Section 5 describes the Ground operations and the facilities that will be available to investigators for data analysis (Scientific software, calibrations).

Section 6 presents the Core Program guidelines.

2. Mission overview

2.1. Introduction

SAX (*Satellite per Astronomia X*) is a major program of the Italian Space Agency (ASI) with participation of the Netherlands Agency for Aerospace Programs (NIVR). Industrial prime contractors are Alenia for the space segment and Nuova Telespazio for the Ground segment. The mission development is supported by a consortium of institutes in Italy together with institutes in The Netherlands and the Space Science Department of ESA. The composition of the consortium is as follows:

- Istituto di Astrofisica Spaziale (IAS), CNR, Frascati and Istituto Osservatorio Astronomico, Università di Roma "La Sapienza"
- Istituto di Fisica Cosmica ed Appl. Informatica (IFCAI) and Unità GIFCO, Palermo
- Istituto Fisica Cosmica e Tecnologie Relative (IFCTR), CNR and Unità GIFCO, Milano
- Istituto per le Tecnologie e Studio delle Radiazioni Extraterrestri (ITESRE), CNR, Bologna and Università di Ferrara
- Space Research Institute of Utrecht (SRU)/SRON, The Netherlands
- Space Science Department (SSD), ESA, Noordwijk, The Netherlands

A collaboration with the Max Planck Institute for Extraterrestrial Physics also exists for X-ray mirror testing and the calibration of the concentrator/spectrometer system. The scientific observational strategy has been defined involving several scientists from institutions outside the Consortium.

SAX is the first X-ray mission (and, in the near-future, the only one) that has the capability of observing sources over more than three decades of energy - from 0.1 to 300 keV - with relatively large area, good energy resolution and imaging capabilities (with a spatial resolution of about 1') in the range of 0.1 - 10 keV. The instrumentation consists of a medium energy concentrator/spectrometer (MECS; 1-10 keV), consisting of three units, a low energy concentrator/spectrometer (LECS; 0.1-10 keV), a high pressure gas scintillation proportional counter (HPGSPC; 3-120 keV), and a phoswich detector system (PDS; 15-300 keV). All these instruments have approximately 1 degree fields of view and point in the same direction. Together they are referred to as the Narrow Field Instruments, or NFI.

The other important capability of the mission is the ability of monitoring large regions of the sky with a resolution of 5' in the range 2-30 keV using two coded-mask proportional counter Wide Field Cameras (WFC). These will allow the long term variability of sources down to 1 mCrab to be studied and the detection of X-ray transient phenomena. The two cameras have 20 x 20 degree FWHM field of views each and point in opposite directions perpendicular to the NFI.

Finally, the anticoincidence scintillator shields of the PDS will be used as a gamma-ray burst

monitor in the range 60-600 keV. The main characteristics of the satellite are summarized in Table 1.

SAX will be launched by an Atlas G-Centaur directly into a 600 km orbit at 3 degrees inclination in the window Mar.19- April 20 1996. The satellite will thus nearly avoid the South Atlantic Anomaly and take full advantage of the screening effect of the Earth's magnetic field in reducing the cosmic ray induced background. Furthermore the choice of this orbit will minimize the modulation of the earth magnetic cut-off and consequently the modulation of the particle induced background. This is an important factor in achieving the necessary sensitivity for observations of weak sources by the high energy experiments, particularly the PDS. Particular care has been taken to minimize systematic effects in the background evaluation, particularly for the HPGSPC and PDS. Both these instruments utilize rocking collimators and active gain equalization, as described in the next section.

The satellite will achieve one arc minute pointing stability. The main attitude constraint derives from the need to maintain the normal to the solar arrays within 30 degrees of the Sun, with occasional excursions to 45 degrees for some WFC observations possible. Therefore during a single orbit the NFI can observe a band of sky 60 degrees wide (50% of the sky) and the WFC a slightly larger region. Observing efficiency will depend on target position due to Earth eclipse (which has a diameter of about 130° at 600 km).

During each orbit up to 450 Mbits of data will be stored onboard and relayed to ground during station passage. The average data rate available to instruments will be about 64 kbit/s, but peak rates of up to 95 kbit/s can be used for parts of an orbit. The satellite will pass over the ground station, placed near the equator in Malindi, Kenia, every orbit. This will allow the prompt operation and control of the satellite. This is particularly important for target of opportunity objects (TOO) that need timely follow up observations. The Operational Control Center (OCC), located in Rome, will be connected to the ground station by relay satellite. The Scientific Data Center will be co-located with the OCC in order to optimize the interaction between the scientific and operational components.

2.2. The instruments

The main characteristics of the SAX payload instruments, described in more detail in chapter 4, are given in Table 2.2. Effective areas are plotted in Fig. 2.2.

The concentrator/spectrometer system consists of four separate concentrator mirror assemblies with a focal length of 185 cm and a position sensitive, Xenon filled, GSPC in the focal plane. The mirror assemblies are composed of 30 nested gold coated, confocal double cone approximation to a Wolter 1 configuration. X-ray test on the flight units have shown a resolution of $40''$ (Half Power Radius, HPR), better than the design goal of 1 arc min. The concentrators are designed to maximize their effective area around 7 keV for studies of iron line emission.

Three of the GSPC's have 50 micron beryllium X-ray entrance windows and are sensitive in the energy range 1-10 keV and are referred to as the Medium Energy detectors (MEGSPC). The scientific model of the MEGSPC has been tested (together with the scientific model of the concentrators) at the Panter X-ray facility, confirming the expected energy resolution (FWHM) of 8 % at 6 keV and a position resolution at the same energy of 0.7 mm FWHM, corresponding to 0.7 arcmin HPR. This position resolution is well matched to that of the concentrators. The background rejection efficiency, based on burst length discrimination, is greater than 99 %. The gain of the detector is monitored by two Fe55 radioactive sources (E=5.9 keV) at the edges of the field of view. A Concentrator together with an MEGSPC is referred to as a MECS.

The fourth GSPC has a 1.25 micron multilayer polyimide window that extends the energy range down to 0.1 keV and is referred to as the Low Energy detector, or LEGSPC. Above 1 keV the energy and the position resolution are similar to those of the MECS units, following the expected $E^{-0.5}$ law as tests on the flight unit have confirmed. The LEGSPC together with its concentrator system is referred to as the LECS.

The High Pressure Gas Scintillation Proportional Counter (HPGSPC) is a new development of a GSPC filled with 5 atmospheres of xenon/helium mixture. This allows the detector to be sensitive between 3 and 120 keV. The cell of the HPGSPC is viewed by an Anger camera arrangement of seven PMTs. The event position is used to correct the event energy with an overall improvement of a factor of two in energy resolution compared to proportional counters. Tests on the flight unit have shown a resolution of 4% @60 keV.

The Phoswich Detector System (PDS) is based on four phoswich units, surrounded at the sides by an active shield of CsI(Na) and with a particle shield of plastic scintillator in front of the entrance window. This instrument has been extensively tested by balloon flights and will extend the energy range of SAX up to 300 keV. The flight units have an energy resolution of about 16% @60 keV.

The lateral shields of the PDS are also used as gamma-ray burst detectors. The limiting sensitivity is 10^{-6} erg/cm² in the nominal range 60-600 keV, and time resolution of up to 0.5 msec is available.

The HPGSPC and PDS utilize rocking collimators, pointing on and off source (with a period of the order of a minute) to monitor the background. In the case of PDS, two of the four units will alternatively point at source and background regions, thus providing a continuous monitoring of the background. The above two instruments also have gain equalization systems. These are based on tagged radioactive sources (time tagged for PDS, position tagged for HPGSPC), that will automatically adjust the high voltage in order to keep the gain of the detectors within 0.25-0.5%.

LECS, MECS, HPGSPC and PDS all point in the same direction and are referred together as the Narrow Field Instruments (NFI)

The Wide Field Cameras consist of two position sensitive proportional counters filled with 2 atmospheres of xenon, which view the sky through a coded mask perpendicularly to the axis of the NFI. They combine large fields of view ($20^\circ \times 20^\circ$ FWHM per unit) with an angular resolution of a few arcmin. Their sensitivity (1 mCrab in 30000 s) will allow the monitoring of faint sources such as AGN, along with their prime objectives, which are to survey the galactic plane and to search for bright X-ray transients.

An important property of the SAX payload is the broad overlapping energy responses of the various instruments. This has been deliberately provided in order to allow a good relative calibration of the instruments to be performed. This is essential in order to obtain the maximum scientific benefit from the SAX instrumentation.

2.3. Scientific objectives

The primary characteristic of SAX is its broad band spectral coverage, with well balanced performances between the low-medium (0.1-10 keV) and medium-high (10-300 keV) energy bands. Given the instrumental capabilities over a wide energy range, SAX can provide significant and unique contributions in many areas of X-ray astronomy such as:

- Compact galactic sources; The shape and variability of the continuum: narrow spectral features especially cyclotron lines as a function of orbital and rotational phase. Ultra-soft sources; discovery and study of X-ray transients.
- Active Galactic Nuclei: spectral shape and dynamics of the variable continuum and of the narrow and broad components from 0.1 to 300 keV in bright objects (soft excess, warm and cold absorption and related O and Fe edges, iron line and high energy bump, high energy cut-off); spectral shape of objects down to 1/20 of 3C273 up to 100-200 keV ; spectra of high redshift objects up to 10 keV
- Clusters of galaxies: spatially resolved spectra of nearby objects and the study of temperature gradients and cooling flows ; chemical composition and temperature distribution as a function of redshift
- Supernova remnants: spatially resolved spectra of extended remnants; spectra of Magellanic Cloud remnants
- Normal galaxies: spectra from 0.1 to 10 keV of the extended emission
- Stars: multi-temperature spectra of stellar coronae from 0.1 to 10 keV.

2.4. Scientific Program: Strategy And Operations

With its nominal lifetime of two years (expected: four years), SAX will be able to perform more than 1000 pointings. While the NFI will be the prime instruments most of the time, the WFC will be periodically used to scan the galactic plane to monitor the behavior of sources above 1 mCrab and to detect transient phenomena. With their large fields of view, the WFC will be able to monitor selected objects when the NFI perform their sequence of pointed observations. We expect to detect about 10-20 bright X-ray transients per year during the WFC observations. The observing program will be flexible enough to accommodate follow-up observations with the NFI of selected TOO. Due to the extremely flexible operating strategy, SAX will be able to acquire a new target within a few hours of its discovery.

SAX observations will be organized on the basis of a "Core Program", devoted to systematic studies paying particular attention to scientific objectives that exploit the unique capabilities of SAX, and a "Guest Observer" program. The time reserved for the Core Program is 80% during the first year of the mission, decreasing in the following years. The Core Program is open for competition only to proposals led by Principal Investigators (PI) belonging to Italian or Dutch institutions, to the Space Science Department of ESA or to the Max Planck Institute for Extraterrestrial Physics of Garching. The Guest Observer program is open for competition to proposals led by PI from any country worldwide. Proposals will be judged and selected, on the basis of their scientific merit and of their feasibility, by a peer committee, the Time Allocation Committee (TAC), under the auspices of the SAX Scientific Steering Committee (SSSC).

In order to allow investigators to fully exploit the SAX data (about 1 Gbyte of data produced every day), software for the scientific data analysis is under development, that will be made available to the community. SAX data will be distributed on tapes, both on the standard 1/2" media, DAT or EXABYTE cassettes. A Scientific Data Center will be set up in Rome near the Operational Control Center, to maintain the data archive, perform routine calibration, maintain and distribute the scientific software and calibrations and provide assistance to observers.

Tab.2.1 Main characteristics of the SAX mission and spacecraft**Orbit**

Type	circular at 3° inclination to the equator
Height	600 km
Period	97 min
Ground contact	11 min per orbit (satellite visible during every orbit)
Lifetime	2 years (nominal); 4 years (expected)
Launch date	Mar.19-Apr.20 1996
Vehicle	Atlas G-Centaur

Spacecraft

Total mass/power	1350 kg/ 800W
payload mass/power	480 kg/ 260W

Pointing

Observing time	typically 10^4 - 10^5 s
stability	1 arc min (three axis stabilized)
reconstruction	< 1 arc min

Telemetry

average/max rate	64/95 kbit/s
tape capacity	450 Mbits
downlink	1 Mbit/s

Tab.2.2 Main characteristics of the SAX instruments

Instrument	Range (keV)	FOV (°FWHM)	Angul. Res. FWHM (arcmin)	Area (cm ²)	Energy Res. (% FWHM)
Concentrators					
1 LECS	0.1-10	0.5	$2 (E/6)^{-0.5}$	20@0.25 keV	$8 \cdot (E/6)^{-0.5}$
3 MECS	1-10			150@ 6 keV	
HPGSPC	3-120	1.1 (coll.)	-	450 (geom.)	$4 \cdot (E/60)^{-0.5}$
PDS	15-300	1.4 (coll.)	-	800 (geom.)	$15 \cdot (E/60)^{-0.5}$
2 WFC	2-30	20x20*	5	250* (through mask)	$18 \cdot (E/6)^{-0.5}$

Narrow Field Instruments (NFI)

* per unit

Figure captions

Fig 2.1 Schematic drawing of the SAX payload and spacecraft

Fig 2.2 Effective area of SAX NFI. For the MECS and LECS we present the effective area of the optics (3 for the ME, 1 for the LE) along with the efficiency of the detectors.

Fig. 2.3 Sensitivity of NFI for 10 and 100 ksec exposure time. For HPGSPC and PDS it is assumed that half of the time the instruments will monitor the background.

Fig.2.1

3. Observation scheduling constraints

3.1. Technical constraints

The main attitude constraint derives from the need to maintain the Solar aspect Angle (SA, defined as the angle between the sun vector and the +X axis of the satellite (the axis normal to the solar panels)) within 30° , with occasional excursions to 45° for some WFC observations. Therefore during a single orbit the NFI (+Z axis) will have a band in the sky of 60° wide available for observations (50 % of the sky), and the WFC's (+Y, -Y axes) a slightly larger region.

Observing efficiency (defined as the fraction of the time the target is observable by the instruments along the orbit) will depend on target position due to the possible eclipse by Earth (which has a diameter of about 130° at 600 km) and the fraction of the time the satellite spends in regions of high particle background near the South Atlantic Anomaly (SAA), where the instruments will be switched off. Thanks to the favourable low inclination orbit, this fraction of time is on average only 5%.

In fig. 3.1 the observability maps give the permissible pointing regions derived from SA constraint (planets not included) in celestial coordinates during the year.

In fig. 3.2 we give the efficiency due to earth occultation as a function of the declination of the source. Note as the sources towards the poles are never occulted by earth.

For targets which are not time constrained, the SAX mission planning team at SDC will take care of scheduling optimization.

Tools for checking visibility constraints are available (Sect.7)

3.2. Time constrained observations

All the observations that are to be performed in defined dates (e.g. coordination with ground and satellite facilities) impose constraints on the mission scheduling reducing the overall efficiency of the observing plan and therefore should be of primary scientific relevance.

In the proposal it is possible to specify the time windows where the observation should be performed. More details can be given in the ADDITIONAL_INFO form (SAO1). To allow more flexibility to the scheduling team, the proposer could identify more than one observing window and should keep the window as large as possible.

The observer is also requested to check the observability of the source in the proposed period using fig.3.1 or the visibility tool (Sect. 7).

Note that due to the unpredictability of the satellite position along the orbit on time scales longer than a month (basically due to air drag) observation of astrophysical events with duration less than the earth occultation time of the source cannot be planned.

3.3. TOOs

Implementing TOO observations imposes non-trivial requirements on the Ground Segment operations and will inevitably have a negative impact on the overall observing efficiency. While the scientific merit of TOO observations in the context of this mission is clearly understood, the level at which they will be feasible in detail and the ensuing reduction in efficiency which will be regarded as acceptable, remains to be assessed.

It should be considered that operational constraints impose a minimum of about 15 hours to acquire the target.

It is necessary that the proponent give in the proposal the identification criteria to classify an event as a specific TOO (e.g. flux thresholds, rise time, spectral shape,...) in order to take appropriate and quick decisions about the follow up observation of the target.

Then the follow up observing plan must be specified, giving the observing plan after the discovery of the event, the pointings duration and the expected Data Collecting Modes (DCM) of the instruments.

TOO follow up observations may be started after an alert from ground based or other satellites' observations. In such a case the PI (or his designated CoI) must contact the SDC team, providing all the necessary and available information.

WFC data will be analyzed every orbit (100 min) as a service on 24 hours shifts by the OCC team to detect X-ray transient phenomena. It is then interest of the observer to give all the information necessary to understand whether the event is falling in the category proposed by the observer.

Figure captions

Fig 3.1a-f Permissible pointing regions in equatorial coordinates for NFI (for WFC are similar but slightly larger, taking into account the 20° FOV of the instruments) for different periods of the year. The forbidden regions are centered in the sun direction (the circle with a central dot along the ecliptic line) and in the antisun direction. The galactic plane is shown by a line

Fig 3.2 Observing efficiency due to earth occultation along one orbit as a function of the target declination.

4. SAX Instruments

4.1. Introduction

This section contains, along with a description of the instruments, the tools necessary to define the feasibility of a proposal. From a given spectrum, the observer can derive the expected count rates and assess telemetry allocation to different instruments and acquisition modes. It is anticipated that for sources fainter than about 0.3 Crab, the telemetry can retain full direct modes (where each event is transmitted with the full information) for all instruments, and the proponents can basically adopt the default modes. In the opposite case the observer should find a trade-off, privileging the information more relevant to the scientific goal (e.g. temporal vs. imaging vs. energy information), by choosing different modes or allocating the telemetry to a subset of instruments.

As for the scientific feasibility we provide plots illustrating the ability of the SAX scientific payload to determine broad and narrow band features (e.g. spectral index determination, line detection) as well as time variability.

If a more detailed assessment of the capability of the mission is required, the observer can use spectral simulation tools (Sect.7)

4.2. Concentrator Optical System¹

4.2.1. Introduction

Each Mirror Unit is composed of thirty nested coaxial and confocal mirrors having thickness from 0.2 to 0.4 mm. The mirrors have a double cone geometry to approximate the Wolter I configuration, with diameters ranging from 162 to 68 mm, focal length of 1850 mm and total length of 300 mm. Each MU has a weight of about 13 Kg.

Due to the large number of mirrors needed for the qualification and for the flight models of the MU and considering the requirements for angular resolution and thickness of the mirror walls, a replica technique by nickel electroforming from mandrels was considered the most appropriate for making the optics: a 1000 Å thick gold layer is evaporated on a superpolished mandrel to provide the X-ray reflecting surface and to separate the electroless nickel of the mandrel from the nickel of the mirror, deposited in an electroforming bath. The separation of the replicated mirror from the master is accomplished by cooling the aluminium mandrel. The following table lists the nominal values of the optical project of the Mirror Units.

Number of nested coaxial double-cone mirrors	30
Mirrors overall length	300 mm
First (input) cone length	150 mm
Second (output) cone length	150 mm
Mirror Unit focal length	1850 mm
Total geometrical collecting area	123.964 cm ²
Total weight of mirrors	8.702 Kg

Mirror Unit characteristics for SAX MECS and LECS instruments.

Two front end stainless steel spiders with eight arms are supported by a tube on which the flange for the interface to the satellite is mounted. The support and the alignment of the nested mirrors are provided by precise grooves machined on the spiders' arms. The diameters of the grooves are within 5 µm of the nominal requested values; the out of roundness error of a single groove and the mutual concentricity errors of the grooves are better than 5 µm.

A silicon compound is used to fix the mirrors and to damp the mechanical vibrations between mirrors and spiders during qualification tests and launch phase.

4.2.2. Performance

The EQM Mirror Unit (spare Flight Model) was tested at the PANTER X-ray facility of Max Planck Institut fuer Extraterrestische Physik, Munich in August 92, the FM1 and FM2

¹Contribution by G. Conti, B. Sacco, L. Chiappetti

in August 93 and the FM3 and FM4 in January 94.

The measurements were made at 0.3 keV (C-K α), 0.9 keV (Cu-L α), 1.5 keV (Al-L α), 3 keV (Ag-L α), 4.5 keV (Ti-K α), 6.4 keV (Fe-K α), and 8 keV (Cu-K α).

4.2.2.1. Effective Area measurements

The geometric collecting area of the MUs is 123.9 cm². The finite distance of the source at the PANTER facility (130 m away from the MU) causes a loss of area because of the divergence of the X-ray beam, that amounts to 15.7 cm². Spider obstruction also diminishes the useful area by the 10.1% and so the utilised geometrical area for the PANTER tests is 97.3 cm².

The measured on axis effective areas are the following:

	0.3 KeV cm ²	0.9 KeV cm ²	1.5 KeV cm ²	3 KeV cm ²	4.5 KeV cm ²	6.4 KeV cm ²	8 KeV cm ²
EQM	84.2	81.4	80.9	54.1	57.6	56.9	37.6
FM1	83.0	80.8	81.7	55.4	59.7	56.9	38.3
FM2	82.4	79.2	80.1	54.8	57.7	55.4	36.7
FM3	82.2	79.8	80.6	55.2	58.1	57.9	38.8
FM4	83.2	79.2	80.9	54.7	57.2	57.7	38.9
theory	84.4	82.2	82.0	47.4	58.0	53.7	37.6

Measured and theoretical on axis effective areas of SAX EQM and FM Mirror Units.

The experimental data have not been corrected to bring the source to infinity and the ray tracing simulations from which the theoretical data are calculated reproduce the configuration utilised at the PANTER facility. The gold reflectivity curves versus grazing incidence angle and versus energy, used for the simulations, were derived from Zombek .

4.2.2.2. Encircled Energy measurements

The imaging characteristics of a MU are defined by the Encircled Energy Function (EEF) that is the fraction of total energy at the focal plane contained in a circle of radius r , versus r . The EEF is derived from the Point Spread Function (PSF), the intensity function of a point source imaged by the MU.

The following table lists the values of the 50%, 80% and 90% energy radius derived from the measured PSF. As for Effective Area, the measured data have not been corrected to bring the source to infinity. The radius are expressed in *arcsec*. With the source at 136 meters, the plate scale is 110.06 arcsec/mm and the focal length is 1874 mm.

	0.3 KeV			0.9 KeV			1.5 KeV		
	r 50 %	r 80 %	r 90 %	r 50 %	r 80 %	r 90 %	r 50 %	r 80 %	r 90 %
	± .2	± 1.0	± 3.5	± .3	± 1.3	± 4.0	± .3	± 1.5	± 5.0
EQM	27.5	61.3	98.5	28.3	63.7	103.7	29.5	67.7	114.1
FM1	27.0	61.3	98.5	-	-	-	28.7	65.8	107.6
FM2	27.2	61.3	98.0	-	-	-	28.8	63.7	101.7
FM3	30.5	71.3	116.9	31.8	72.8	119.1	32.1	75.1	124.1
FM4	32.1	73.5	120.5	31.8	74.0	122.2	33.6	78.9	133.9

	3 KeV			4.5 KeV			6.4 KeV		
	r 50 %	r 80 %	r 90 %	r 50 %	r 80 %	r 90 %	r 50 %	r 80 %	r 90 %
	± .3	± 2.0	± 7.0	± .4	± 2.3	± 8.5	± .5	± 2.5	± 9.0
EQM	32.1	76.9	138.7	35.2	90.0	172.5	39.3	106.2	205.0
FM1	32.0	79.6	147.7	34.9	92.2	180.8	40.1	111.5	217.6
FM2	31.7	74.4	129.9	34.2	83.8	153.8	38.4	101.2	198.4
FM3	34.5	84.0	151.4	37.8	103.8	223.5	40.4	111.4	214.7
FM4	35.2	87.2	157.9	38.6	98.9	191.2	41.7	112.0	217.9

	8 KeV		
	r 50 %	r 80 %	r 90 %
	± .5	± 3.0	± 9.5
EQM	40.0	110.6	210.7
FM1	42.7	122.1	226.8
FM2	40.6	109.7	212.7
FM3	41.2	113.8	213.4
FM4	40.8	110.8	207.8

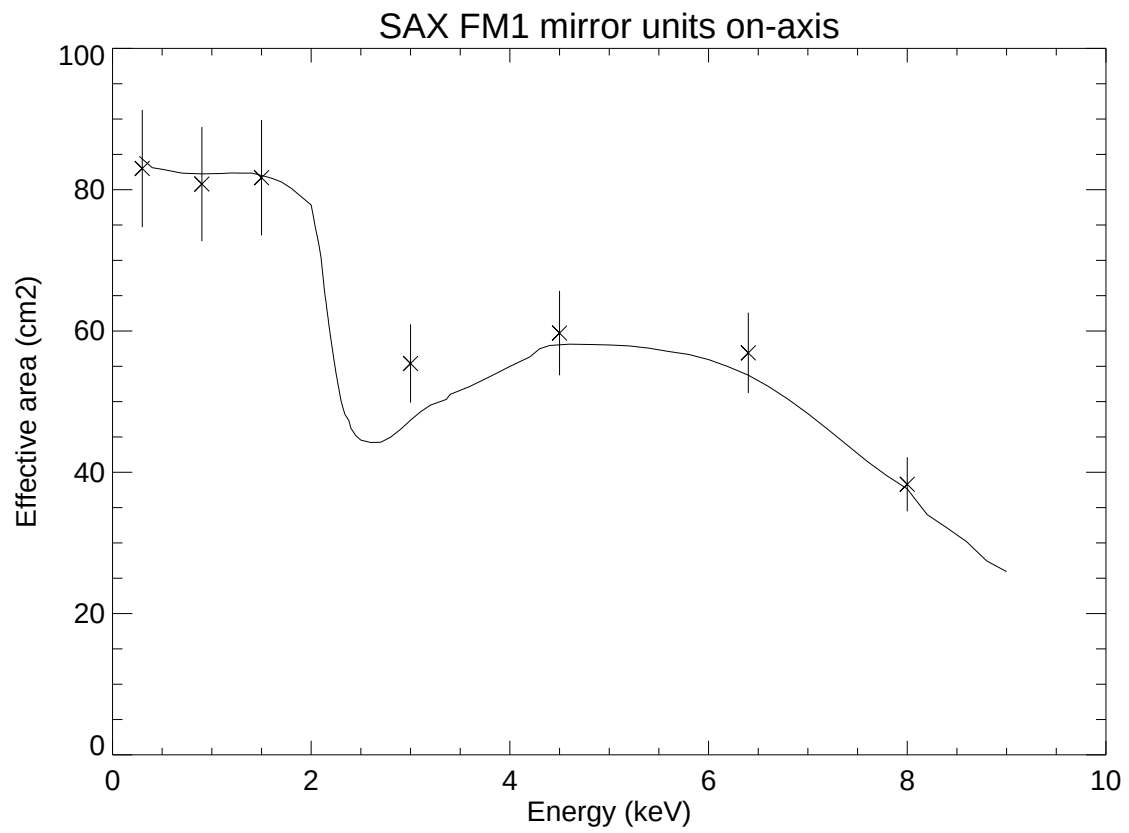
Measured 50 % , 80% and 90% Energy Radius of SAX EQM and FM Mirror Units.

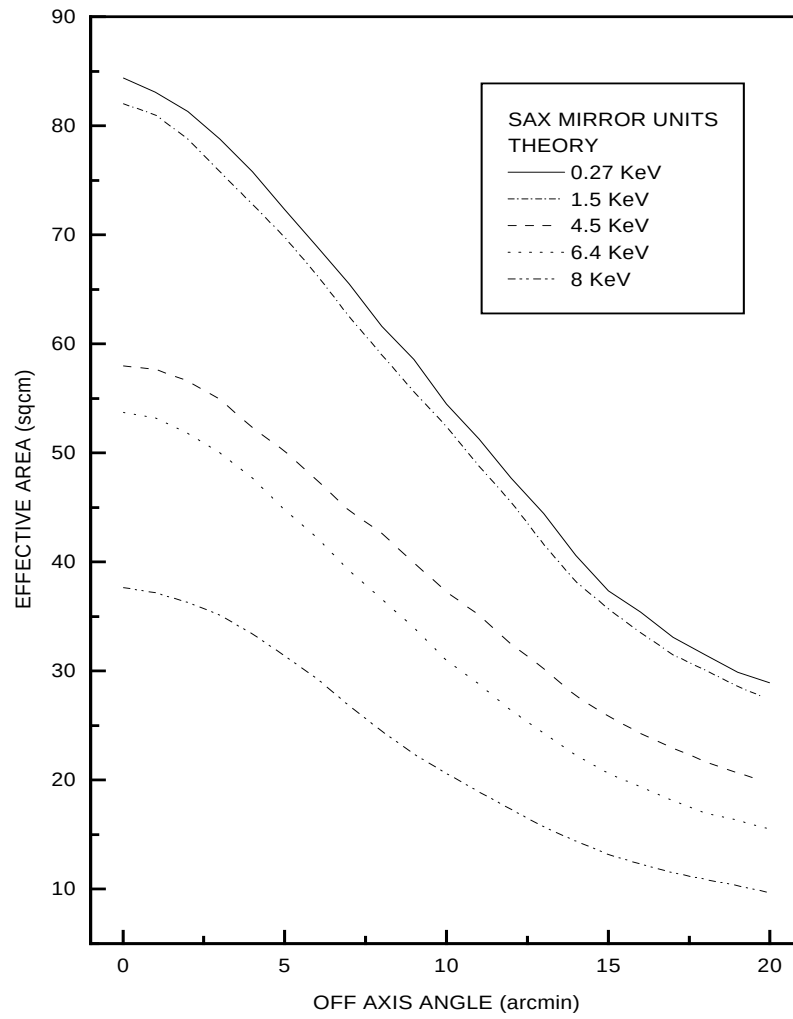
Figure captions

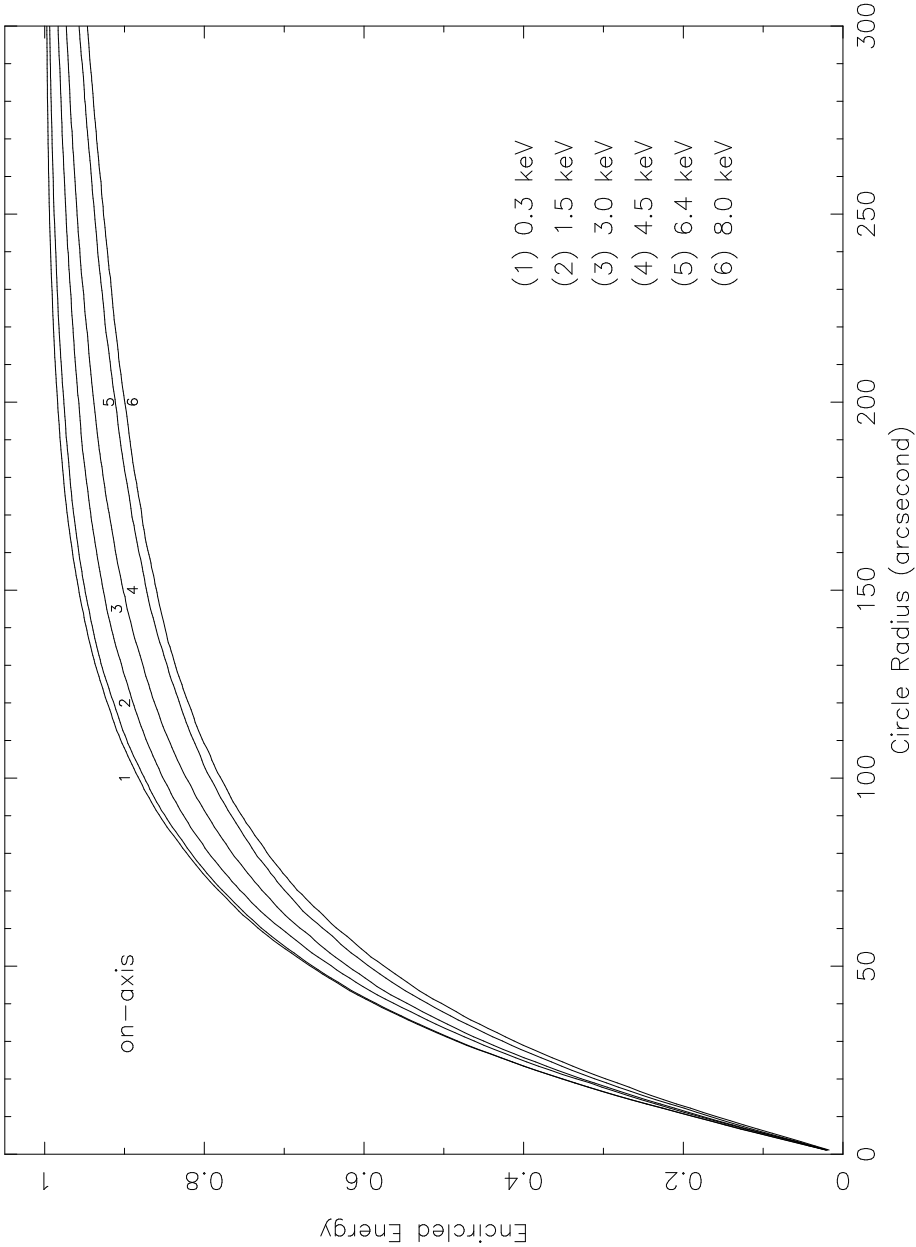
Fig 4.2.1 Effective area of one mirror unit on axis

Fig. 4.2.2 Effective area of one mirror unit for different energies as a function of the off-axis angle

Fig. 4.2.3a-d Encircled energy at different energies and off axis angles as a function of the circle radius

**Fig. 4.2.1**

**Fig.4.2.2**



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Fig. 4.2.3a

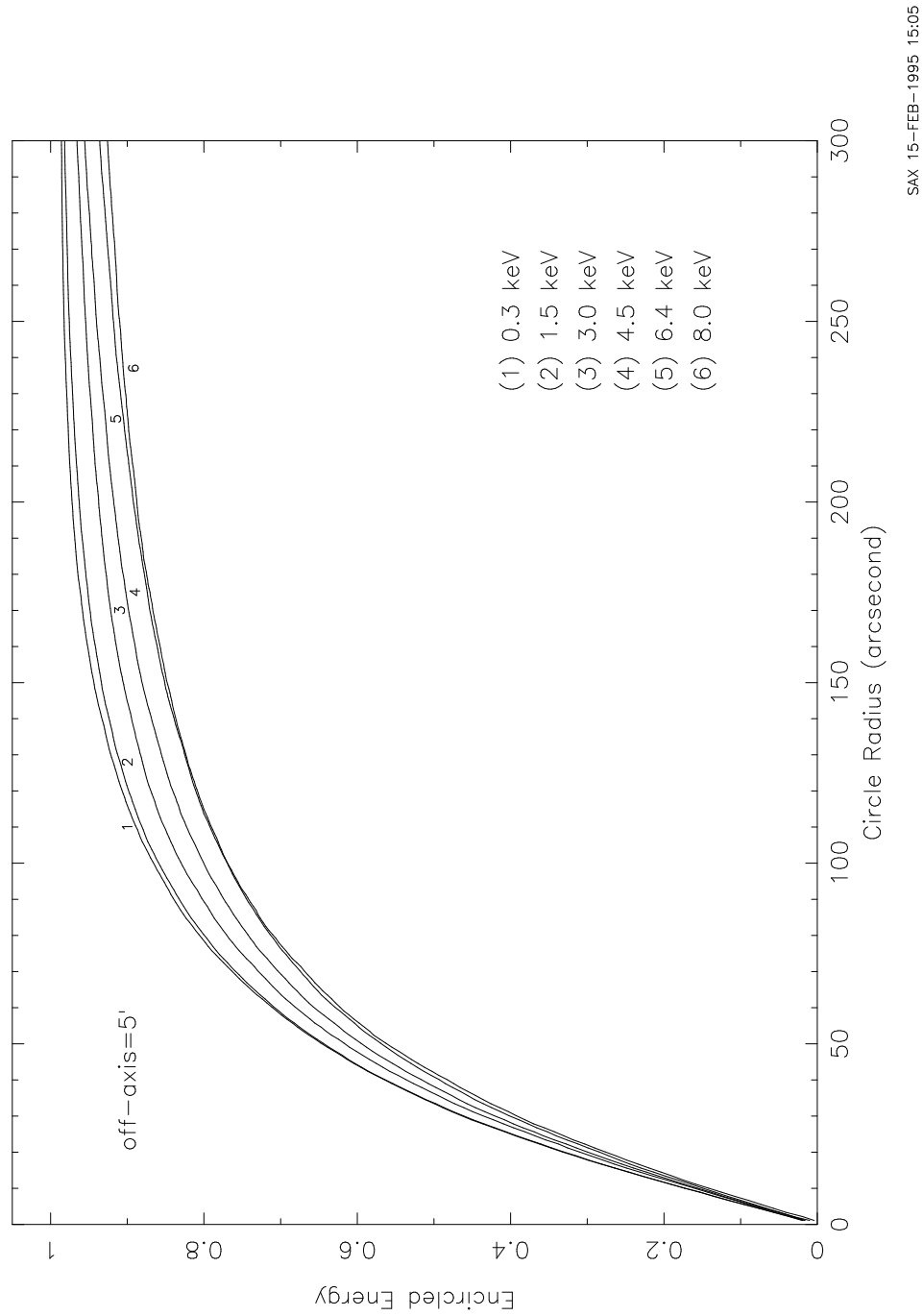
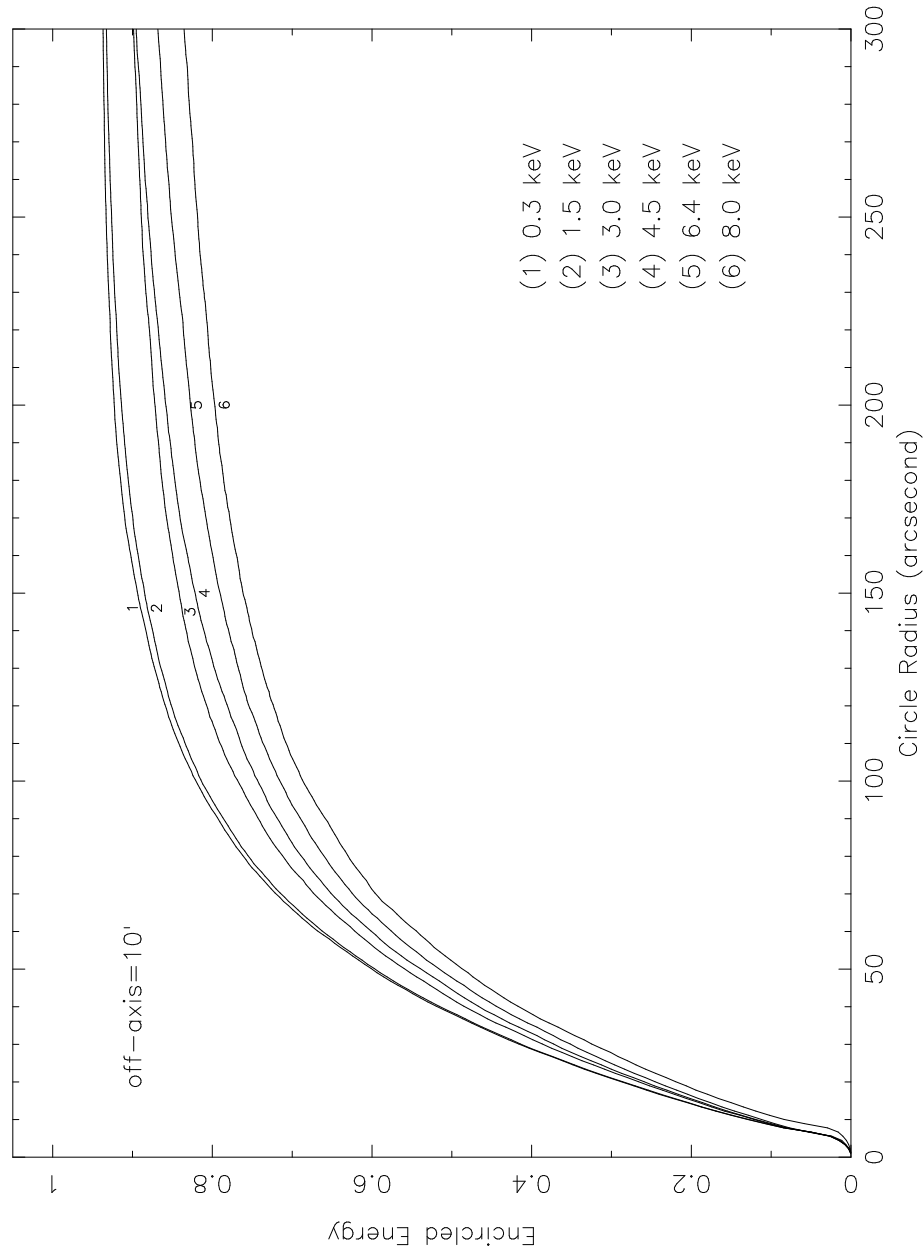


Fig. 4.2.3b



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Fig. 4.2.3c

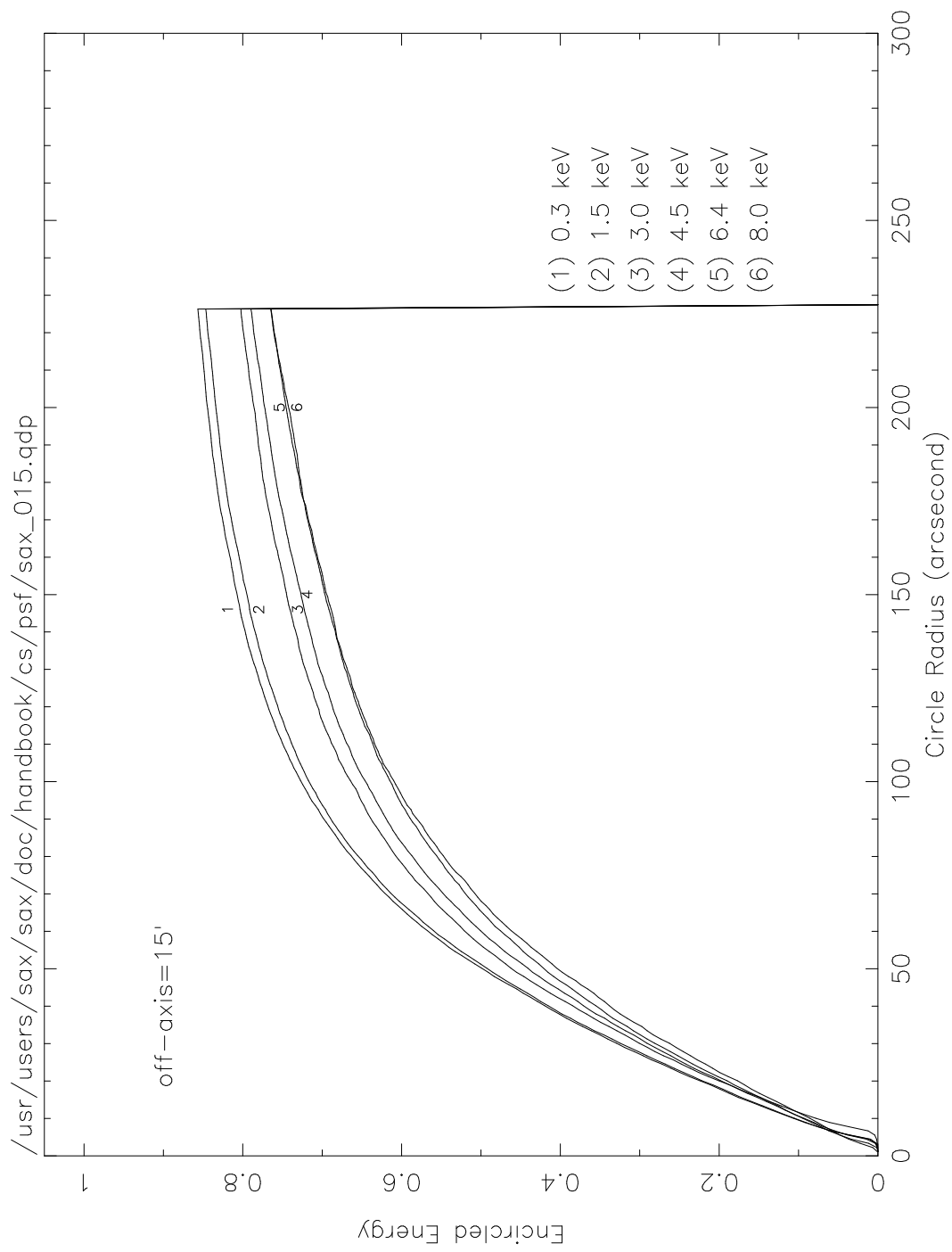


Fig. 4.2.3d

4.3. LECS²

4.3.1 Introduction

Behind one of the concentrator systems on SAX is a low-energy imaging GSPC, or LEGSPC, that extends the energy response of SAX down to 0.1 keV. The LEGSPC together with its concentrator system is referred to as the LECS. Figure 4.3-1 shows a schematic of the LEGSPC. The instrument is divided into Detector, Gas and Electronic Units.

The main goal to the LECS is to perform spectroscopy of on-axis point-sources in the energy range 0.1 - 10 keV. The design and calibration of the detector has been optimized to this goal, and it is worth noting that the energy resolution of the detector is better than that of current CCD detectors below ~0.5 keV.

The low-energy response has been achieved by the use of an extremely thin gas cell entrance window and by dispensing with separate drift and scintillation regions in the cell. This is necessary because conventional GSPCs suffer from poor performance at low-energies due to the loss of significant numbers of photo-electrons to the window. The driftless design of the LECS minimizes such losses since the electrons are always subjected to a high electric field.

The method of operation of the detector is similar to that of a conventional GSPC. An X-ray which is absorbed in the detector cell gas liberates a cloud of electrons. A uniform electric field causes scintillation of the xenon gas as the electrons travel towards the grid. Light from these scintillations is detected by a PMT mounted at the rear of the cell. The amount of light produced is proportional to the energy of an incident X-ray but, unlike a conventional GSPC, also depends on the depth the X-ray penetrated into the gas cell before being photoabsorbed. This depth is determined by measuring the duration of the scintillation light and is referred to as the burstlength. An X-ray absorbed directly below the entrance window will have a long burstlength, while one absorbed close to the exit window will have a short burstlength.

The LECS concentrator system is number FM3. Details of its performance can be found in Section 4.2 and are not discussed further in this section. The LECS also includes a Plasma Protection Grid that will be energized with +28 Volts to repel any positive ion that might be attracted to the negative potential of the detector upper surface. The grid is located just below the concentrator systems.

4.3.2 Detector Unit Description

²Contribution by A. Parmar

The Detector Unit is the 'heart' of the instrument and contains an imaging gas scintillation counter with the necessary support electronics for operation. The Detector Unit (Figure 4.3-2) consists of the following components:

- **Gas Cell.** This is a 114 mm diameter ceramic cylinder of depth 50 mm with a metallic top disk and lower flange. A Titanium support for the entrance window and calibration sources is mounted on the top disk. The cell is sealed on the underside by a transparent 4mm thick Suprasil exit window. A honeycomb grid is located just above the exit window. The cell contains xenon at a nominal pressure of 1.2 bar. At the front of the cell there is an extremely thin entrance window (see below) which allows the passage of X-rays from the concentrators into the cell.
- **Plasma Protection Window.** This seals the front chamber against plasma ingress. It has a multilayer construction (Figure 4.3-3) similar to that of the entrance window, but with a hexagonal Polyimide support grid that is transparent at energies >3 keV.
- **Entrance Window.** The 20 mm diameter entrance window cross-section is shown in Figure 4.3-4 and consists of 1.25μ of Polyimide, 0.044μ of aluminium and 0.035μ of aluminium nitride. The purpose of the aluminium/aluminium nitride multilayers is to act as gas permeation barriers. The aluminium layers significantly reduce transmission in the ultra-violet, visual and infra-red regions while the Polyimide gives the membrane much of its mechanical strength.
- **Window Support Structure.** In order to support the window against pressure differences, a support structure is glued to its external surface. This is in two parts; a 25μ deep, 25μ wide fine tungsten grid and a coarser strongback. The dimensions of the grid are shown in Figure 4.3-5 and those of the strongback in Figure 4.3-6.
- **Getter.** GSPCs are extremely sensitive to gas impurities and a Getter is included in the gas cell to passively absorb small amounts of impurities in the gas. It is also possible to activate the Getter during flight in case passive cleaning is insufficient.
- **Calibration Sources.** Two Fe^{55} radioactive sources (which produce Mn $k\text{-}\alpha$ X-rays with an energy of 5.9 keV) are mounted on the upper face of the gas cell. Each source is mounted 23 mm from the center of the entrance window (i.e. outside of the normal field of view of 10 mm radius) in the $+X,-Y$ and $-X,+Y$ detector quadrants. The sources provide a continuous calibration of the position and energy gains and resolutions of the instrument. Each collimated source is separated from the detector gas by a 500μ thick beryllium window and produced 20 counts s^{-1} in October 1994 with a half-life of 2.7 years.
- **Photomultiplier Tube (PMT).** The PMT is a ruggedized Hamamatsu R5218 tube with a 2.8 mm thick quartz entrance window of 60 mm diameter contained in a mu-metal housing to shield it from external magnetic fields. Nine anodes, each of 13 x 13 mm square are positioned in a 3 x 3 configuration each with a separation of 1 mm. The anodes are operated as an Anger camera to provide spatial information. The cathode is a special

bialkali with a spectral response from 160 to 600 nm. There are 15 proximity mesh dynodes. Each anode provides a separate output which is labelled as A1 to A9 in Figure 4.3-7.

A3	A2	A1
A6	A5	A4
A9	A8	A7

Figure 4.3-7. The PMT Anode Layout.

The above view is looking in the direction of the concentrators through the PMT. The spacecraft +X axis is towards the left and the +Y axis towards the top of the page.

- **Front Chamber.** In order to protect the thin windows during ground testing and launch, the gas cell is completely enclosed by a chamber, or front cover. A thin Beryllium disk is mounted on the interior upper-surface of the cover. The chamber includes a spring loaded shutter, an opening mechanism and micro switches to detect open and closed positions. Following launch, the shutter will be irreversibly opened to allow X-rays to enter the gas cell.
- **Low Pressure Transducer.** This measures the gas pressure in the gas cell in the range 0.0 - 1.2 bar.
- **Thermistor.** This is mounted on the Detector Unit mounting flange adjacent to the PMT entrance window and used to monitor the temperature of the unit.
- **HV Power Supplies.** These provide HV for Scintillation in the gas cell and for the operation of the PMT. The cell output voltage is commandable in 31 steps between –12 kV and –20 kV and that of the PMT between 0.8 and 1.5 kV in 255 steps. The power supply design is based on a flyback converter followed by an 8 stage Cockcroft-Walton multiplier. The HV generated by the multiplier is filtered by a triple resistive-capacitive network to produce output ripple of <0.1% (peak to peak). Upon switch-on, or when changing voltage levels, the output voltage takes 5 seconds to stabilize to the required level. The HV supplies have associated monitors, the outputs of which are proportional to the HV level.
- **Detector Electronics (DEL).** Each of the nine PMT anode signals (A1 to A9) are fed to separate charge amplifiers, the outputs of which are provided to the summing amplifiers from which four output signals are derived:

$$S_a = A1+A2+A3+A4+A5+A6+A7+A8+A9$$

$$S_x = A1+A4+A7-A3-A6-A9 + 0.5 \times S_a$$

$$S_y = A1+A2+A3-A7-A8-A9 + 0.5 \times S_a$$

$$S_v = A5$$

These four signals are passed to the Electronics Unit for further processing. S_x and S_y provides event position information, S_a is used to determine the amplitude, or energy, of an event while S_v provides a measure of the light distribution in the detector and is used to distinguish between particle events (which may appear extended) and true X-ray events (which are point-like). Note that $+S_x$ corresponds to the spacecraft $-X$ direction, and $+S_y$ to the $+Y$ spacecraft direction.

4.3.3 Gas Unit Description

Because of the possibility of leakage through the gas cell entrance window, or contamination of the cell gas, the LECS includes a gas supply system. In normal operations the Gas Unit is disabled. It will only be operated if needed and its description is only included here for completeness.

The GU allows monitoring and control of the gas pressure inside the cell. If the pressure is below a set limit, the gas can be automatically replenished from the high pressure reservoirs. Conversely, if the cell gas pressure exceeds a set limit, the pressure can be automatically reduced. The Gas Unit also provides the capability to completely vent and refill the cell gas. In addition, automatic switching into a safety mode if the gas cell pressure exceeds a pre-set safety limit can be enabled. The Gas Unit control electronics is contained within the Electronics Unit. The Gas Unit consists of:

- **High Pressure Reservoirs.** Two identical 0.5 liter titanium reservoirs which store xenon gas at an initial pressure of 20 Bars.
- **Input Valve.** This non-latching valve allows gas to enter the cell. It is actuated in pulse mode by command from the EU. The pulse duration is settable by ground command in order to minimize the number of actuations.
- **Vent Valve.** This pulsed non-latching valve allows gas to escape from the cell, so reducing the pressure. The operation of the valve is controlled by the EU.
- **High Pressure Transducer.** This monitors the gas pressure remaining in the gas reservoirs in the range 0 - 20 bars. It is the "Reservoir Pressure" parameter in the HK Telemetry.
- **Thermistor.** This is used to monitor the temperature of the GU. It provides the "Reservoir Temperature" parameter in the HK Telemetry.

4.3.4 Electronics Unit Description

The Electronics Unit provides the electrical interface between the instrument and the

spacecraft. It is a single box mounted about 1 meter from the Detector and Gas Units. It has the following functions:

- Normalization of the pre-amplified summed signals delivered by the DEL.
- Qualification of the signals based upon a settable low-level Energy threshold.
- Discrimination of the normalized signals using settable amplitude windows and processing of valid and invalid events via ratemeters.
- Conversion of the pulse lengths of the summed signals to a measurable amplitude signal.
- Conversion of the pulse related amplitudes and HK data into digital values.
- Collection, formatting and transmittal of the experimental data via the spacecraft data bus to the spacecraft data handling systems for re-transmission to the ground.
- Reception and distribution of both ground and on-board generated commands within the instrument.
- Control of the Gas Unit and shutter operation.
- Distribution and conversion of the power from the spacecraft to the various assemblies within the LEGSPC.
- Temperature monitoring via a built-in thermistor.

4.3.5 Instrument Performance

4.3.5.1 Introduction

The overall characteristics and performance of the LECS are summarized in Table 4.3-1

Table 4.3-1. SAX LECS Characteristics

Field of View	40' diameter circular
Window Size	20 mm diameter
Detector Gas	Pure xenon
Operating Pressure	1.2 bar at 20° C
Effective area at 7.0 keV	50 cm ²
Energy Response	0.1 - 10.0 keV
Energy Resolution	$8.0 * (E/6 \text{ keV})^{-0.5}$ FWHM %
Position Resolution	$2.1 * (E/6 \text{ keV})^{-0.5}$ FWHM arcmin
Window Support Structure Transmission	80% (on average)
Maximum Throughput	2000 counts/s
Time Resolution	>16 μ sec
Image size	256 x 256 pixels
Image Pixel Size	17.4" x 17.4" square
Energy Spectra	1024 Channels
Burstlength Spectra	256 Channels
Veto Signal Distribution	256 Channels

4.3.5.2 Comparison with the MECS

The LECS has certain advantages and certain disadvantages compared to the MECS. Its principle advantages are:

- A response in the energy range 0.1 - 1.3 keV.
- No degradation in performance due to loss of electrons to the window (the so-called "Inoue" effect).

The low-energy response comes at the price of considerable complexity, both in terms of the LECS hardware and the analysis procedures that are required to interpret LECS data. The principal disadvantages of the LECS compared to the MECS are:

- There is only one LECS, compared to three MECS, so the overall effective area is smaller.
- The effective area of the LECS is further reduced by the strongback and grid that produce an **average** obscuration of 20%. Unfortunately, this obscuration is both position and energy dependent. The effects of convolving this dependence with any unresolved spacecraft motions are, as yet, undetermined.
- The FOV of the LECS is smaller than that of the MECS (20' rather than 30' radius).
- Because of the driftless configuration, the expected range of Burstlength signals is higher than for a conventional GSPC. Since Burstlength is used as background

discriminator, this means that the LECS background will be higher than that of a single MECS.

- The effects of penetration in the gas cell cause off-axis images to be distorted. This is illustrated in Figure 4.3-8 which shows a multi-pinhole exposure at an energy of 6.4 keV. The distortion of the image around the edge of the FOV is caused by the penetration of the X-rays into the detector cell. This effect results from the driftless design of the LEGSPC gas cell. The events at top left and bottom right of the image are from the two Fe^{55} calibration sources.

4.3.5.3 Effective Area

At low energies, the response of the LECS is limited by the transmission through the gas cell and plasma protection windows, while the high energy limit is caused by the loss of reflectivity of the concentrator system. The total on-axis efficiency of the LECS is shown in Figure 4.3-9. This includes the effects of mirror efficiency, plasma protection window and grid transmission, obscuration due to the window support mechanism, entrance window transmission and detector absorption efficiency. The large jump at 0.28 keV is due to the carbon k-edge, while the structure between 2 and 3 keV is from edge effects in the gold mirror coating. At the edge of the FOV (i.e. an off-axis angle of 20°) the effective area is 0.41 that at the center.

Great care has been taken to ensure a good calibration of the LECS. The philosophy has been to separately calibrate each of the major components and then to confirm this calibration at System Level in a dedicated Calibration Campaign at the Panter Facility that took place in November 1994. The major components affecting the LECS efficiency are:

- **Mirror Efficiency.** The LECS mirror system is number FM3. Details of its performance can be found in Section 4.2. A major uncertainty is the depth and form of the Gold absorption edges between 2 - 3 keV.
- **Plasma Protection Window.** This seals the front of the detector cover against plasma ingress. Its construction is shown in Figure 4.3-3. The transmission of the flight window has been measured at the BESSY synchrotron facility. 500 energy measurements were made at the center of the window between 0.1 and 1.8 keV. The spatial uniformity was investigated by measuring the transmission in three energies in two grids of 22×22 positions. In one grid the position separation was 1 mm and in the second, 0.5 mm. These measurements indicate that the variation in transmission with position is $< 1\%$ rms.
- **Entrance Window Support Structure.** The construction of the support structure is shown in Figures 4.3-5 and 4.3-6. The grid and strongback together obscure an **average** of 20% of the incoming X-rays. Unfortunately, this obscuration depends on both position and X-ray energy in a complex way. The energy dependence arises because of the finite strongback height which casts a shadow around the strongback since the incident X-rays do not arrive exactly normally. Since the average X-ray incidence angle is energy dependent,

this shadowing is also energy dependent. In addition, the PSF of the concentrators is broader at higher energies. This results in a larger area of support structure being illuminated at higher energies, so producing an additional energy dependence.

Figure 4.3-10 illustrates how the LECS count rate varies during a scan along the window Y axis at 6.4 keV. Scans covering the central 4 mm of the window in the X, Y and diagonal directions were made at 0.28 and 6.4 keV. In the central 1.5 mm, the response of the LECS varies by <5% due to obscuration by the fine grid. Obscuration by the strongback ribs result in 15% reductions in count rate at this energy. The overall gradient in the count rate is caused by misalignment of the detector, and should not be seen from cosmic sources. Ray-tracing of the mirror and support structure performance will allow these effects to be characterized over the entire window area.

- **Entrance Window Transmission.** A cross section through the entrance window is shown in Figure 4.3-4. In order to measure the transmission of the window the series of measurements marked by crosses in Figure 4.3-11 were made at the BESSY synchrotron facility. Note that the transmission has only been measured in the central 3 x 3 strongback squares (shown as thick lines in Figure 4.3-11) which corresponds to a square of 12' x 12'. Between 18 and 30 energies in the range 0.1 - 1.8 keV were used with a beam size small enough to fit into the individual grid squares (shown by the dotted lines). In addition, high resolution measurements at 500 energies between 0.1 - 1.8 keV were made at five locations. The rms variation in transmission with position is <3%.

- **Detector Efficiency.** Analysis of synchrotron and Panter data reveals that the Driftless design is very successful and there is no evidence for loss of electrons to the window (see e.g., Figure 4.3-12). This means that the in the range 0.1 - 10.0 keV, the detector efficiency is always close to 1.0.

4.3.5.4 Deadtime Losses

There is a small deadtime in the LECS due to the time it takes to convert the analogue signals to digital values. While this is occurring, the instrument is insensitive to further events. For a 1 Crab source the loss corresponds to ~10% of events. A deadtime ratemeter records the fraction of time that the instrument is insensitive, and this value is placed in the HK telemetry every 1 second.

4.3.5.5 Energy Resolution

The energy resolution over most of the FOV of the LECS is given approximately by:

$$\Delta E/E = 8.0 \times (E/6 \text{ keV})^{-0.5} \% \text{ FWHM}$$

Because of the driftless design and edge effects in the xenon detector gas, the resolution function is not a simple Gaussian distribution, especially at high-energies. Figure 4.3-12 shows line profiles for C (0.28 keV) and Cu_K (8.04 keV). The lack of an appreciable low-

energy tail in the low-energy measurements demonstrates that loss of electrons to the entrance window is insignificant. The detailed shapes of the resolution functions and their energy and burstlength dependences will be taken into account in the LECS response matrix.

4.3.5.6 Position Resolution

The position resolution of the LECS is given by:

$$\Delta P = 2.1 \times (E/6 \text{ keV})^{-0.5} \cdot \text{FWHM}$$

At 6 keV this relation is valid in the central 8' of the FOV. The range of validity increases with decreasing energy, such that at 0.28 keV it is valid over the entire FOV. Figure 4.3-8 illustrates the complexity in determining the position resolution outside of the range of validity since the LECS images are strongly non-axisymmetric.

4.3.5.7 Background Counting Rates

The background in the LECS consists of components induced by incident particles and the cosmic X-ray background and, at times, scattered solar X-rays. The particle induced background likely to be experienced by the LECS in orbit is given in Table 4.3-2. Based on the experience of the ASCA GIS, this is assumed to be a factor 3 higher than that measured in the laboratory.

The spectrum of the cosmic X-ray background spectrum is complex. Above about 1 keV it can be modeled by $f(E) = 8.5 \times E^{-1.4} \text{ ph cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$. At lower energies, the spectrum steepens and may be represented by $f(E) = 13.4 \times E^{-2.12} \text{ ph cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$. For the FOV of the LECS this results in count rates for the cosmic X-ray background of $7.2 \times 10^{-5} \text{ counts s}^{-1} \text{ arcmin}^{-2}$ in the energy range 0.1 - 1.0 keV and $5.4 \times 10^{-5} \text{ counts s}^{-1} \text{ arcmin}^{-2}$ above 1.0 keV.

The scattered Solar background consists of X-rays of solar origin which scatter off the residual Earth atmosphere along the LECS's line of sight. Since these X-rays arise as diffuse emission external to SAX, they are focused in exactly the same way as cosmic X-rays. In the LECS energy range below 0.28 keV the dominant process is Thomson scattering (from oxygen, helium and molecular hydrogen). Above 0.28 keV, fluorescent scattering dominates (from molecular nitrogen K- α at 0.4 keV and atomic oxygen K- α at 0.54 keV). This will appear as an extra component to the background when the LECS' line of sight subtends the Sun lit atmosphere. The size of the effect can be gauged from Rosat PSPC observations which detected between 4×10^{-5} and $6 \times 10^{-3} \text{ counts s}^{-1} \text{ arcmin}^{-2}$ in the 0.1 - 1.0 keV energy range. Scaled to the LECS this predicts a count rate of between 0.012 and 1.8 counts s^{-1} .

The background counting rates are summarized in Table 4.3-2. It should be noted that in the broad band (0.1 - 10.0 keV) range, the background from cosmic X-rays and particle events are expected to be comparable. At low (<1.0 keV) energies, the cosmic X-ray

background is expected to dominate.

Table 4.3-2. LECS Background Counting Rate Summary

Component	Counts (s^{-1} arc minute $^{-2}$)
0.1 - 10.0 keV	
Particle Background	1.6×10^{-4}
X-ray Background	1.3×10^{-4}
Scattered Solar X-ray Background	9.6×10^{-6} to 1.4×10^{-3}
0.1 - 1.0 keV	
Particle Background	1.6×10^{-5}
X-ray Background	7.2×10^{-5}
Scattered Solar X-ray Background	9.6×10^{-6} to 1.4×10^{-3}

4.3.5.8 UV and Optical Transmission

The gas cell and plasma protection windows are extremely good UV filters, but have a transmission as high as 10^{-4} in the optical. This will result in a slight 'leakage' for bright stars that will appear as background counts in the lowest energy channels. The effect will be calibrated post-launch.

4.3.5.9 Gain

The relative gain of the instrument is monitored using two 5.9 keV Fe^{55} calibration sources located outside of the FOV (see Figure 4.3-8). Since the gain of the instrument varies with offset angle, the sources only provide a relative calibration in the FOV. The gain varies smoothly with position in the FOV, being highest close to the center and falling to ~95% of that on-axis for an off-axis angle of 20'. The overall gain also depends on temperature, increasing by 1.4% per degree decrease in temperature. It is expected that this variation can be accurately modeled using the calibration source data.

4.3.5.10 Timing Accuracy

While the LECS time tags events to a precision of 16 μsecs , care must be taken in the interpretation of any detected variability. This is because variations in satellite pointing position during an observation may produce a modulation of the detected count rate due to the complex obscuration effects of the tungsten strongback and grid. The magnitude and impacts of this effect will be calibrated post-launch.

4.3.6. Feasibility

This section provides details of the performance of the LECS in order that potential users

can quantify the feasibility of proposed observations.

4.3.6.1 Detection Cell Size

A detection cell of radius 6.1' has been used for estimating sensitivities etc. This cell size was chosen to allow 80% of C_K (0.28 keV) X-rays to be included. This cell corresponds to a radius of 0.33 cm on the detector entrance window.

4.3.6.2 Minimum Detectable Count Rates

The minimum detectable count rate for the LECS depends on the background counting rate and the size of detection cell used. The minimum detectable count rate, $I_{\min}$, can be estimated using:

$$I_{\min} = t^{-0.5} \left(\frac{k_{\sigma}^2 B_{\text{cell}}}{f^2} + \frac{N_{\min}^2}{t} \right)^{0.5}$$

Here k_{σ} is the required significance threshold (i.e. signal to noise ratio; taken to be 5), B_{cell} the background count rate in the detection cell, $N_{\min}$ is the minimum number of photons required to constitute a detection, f is the fraction of photons falling in the detection cell and t is the integration time. A minimum of 10 counts for a source detection ($N_{\min}$) has been assumed for the photon limited case. Figure 4.3-13 shows minimum detectable count rates for the energy ranges 0.1 - 1.0 keV and 0.1 - 10.0 keV. The background rates for these calculations are those given in Table 4.3-2.

4.3.6.3 Expected Count Rates

The expected LECS count rate depends sensitively on the assumed incident spectrum which will be fairly well known for the majority of SAX targets. In order to facilitate count rate calculations, the following spectral models are considered:

1. Power-law spectrum with photon index α .
2. Raymond-Smith Plasma spectrum where kT is the temperature in keV.
3. Blackbody spectrum where kT is the temperature in keV.

In Figures 4.3-14 to 4.3-19 the energy to counts conversion factors (ECF) are shown for the above spectral models and for the energy ranges 0.1 - 1.0 keV and 0.1 - 10.0 keV. The ECF is the factor that the unabsorbed source flux (in units of $10^{-11} \text{ erg cm}^{-2} \text{ s}^{-1}$ in the appropriate energy band) has to be multiplied by in order to obtain the expected LECS on-axis count rate.

These Figures are used as follows:

1. Calculate the expected source flux F_s (in units of $10^{-11} \text{ erg cm}^{-2} \text{ s}^{-1}$) in the LECS in either the 0.1 - 1.0 keV or 0.1 - 10.0 keV range for $N_H=0.0$.
2. Determine the expected absorption column density.
3. With the assumed values of N_H and power-law index or kT read from one of Figures

4.3-14 to 4.3-19 the value of the ECF.

4. Multiply F_s by the ECF to obtain the expected on-axis LECS count rate.

As an Example:

In order to determine the expected on-axis 0.1 - 10.0 keV count rate for the Crab Nebula in the LECS, do the following:

1. For an assumed spectrum of $9.8 \times 10^{-2.08} \text{ ph cm}^{-2} \text{ s}^{-1}$, unmodified by low-energy absorption, calculate the flux in the energy range 0.1 - 10.0 keV to be $7.28 \times 10^{-8} \text{ erg cm}^{-2} \text{ s}^{-1}$ using e.g., the flux command in XSPEC.
2. Read the ECF for the above spectral slope and an N_H of $3 \times 10^{21} \text{ atoms cm}^{-2}$ (appropriate to the Crab Nebula) to be 0.055 from Figure 4.3-14.
3. Multiply the ECF by the flux in units of $10^{-11} \text{ erg cm}^{-2} \text{ s}^{-1}$ to obtain an expected count rate of 365 s^{-1} .

4.3.6.4 Sensitivity to Line Features

The LECS sensitivity to line emission has been calculated for lines at 0.57 and 6.7 keV for a range of underlying continuum strengths and for observation durations of 10^4 and 10^5 seconds (Figures 4.3-20 and 4.3-21). The sensitivity of an instrument to a line feature, I_L , can be expressed as:

$$I_L = \frac{K_\sigma}{A(E) F(\Delta E)} \left(\frac{\Delta E I_c(E) A(E) + B_{\text{cell}}}{t} \right)^{0.5} + \frac{N_{\text{min}}}{A(E)t}$$

where $A(E)$ is the effective area at energy E , $F(\Delta E)$ is the fraction of line photons falling in the resolution element (taken to be 0.67), I_c is the continuum flux at the line energy in $\text{ph cm}^{-2} \text{ s}^{-1} \text{ keV}^{-1}$, B_{cell} is the background flux in counts s^{-1} per detection cell, ΔE is the energy resolution at energy E in keV, k_σ the significance in the background limited case (taken to be 5) and N_{min} the minimum number of photons required in the photon limited case (taken to be 10). The particle and cosmic X-ray background count rates given in Table 4.3-2 are used to derive the curves presented in Figures 4.3-20 and 4.3-21.

4.3.6.5 Sensitivity to Source Variability

The sensitivity of the LECS to source variability is illustrated in Figure 4.3-22. This shows the time, T , taken to detect a change in source flux of $Y\%$ (i.e. $Y=0.2$ corresponds to a 20% change in source flux), where S is the source count rate, B the background counting rate and k_σ the required significance.

$$T = \frac{k_\sigma^2 (S+B+S \times Y)}{(S \times Y)^2}$$

Thus for a source and background count rates of 0.2 and 0.05 s^{-1} , respectively, 16,800 sec

are required to detect a 10% variation in source flux at 5σ confidence.

4.3.7 Instrument Operation

During viewing intervals, the Cell and PMT HV settings will be set to their nominal values of -20 kV and 1.080 kV, respectively. These settings result in the calibration sources appearing at PHA channel ~400 under normal operating conditions.

Following the instrument commissioning phase, it is expected that the most appropriate analogue and digital thresholds for the LECS will have been selected. It is not expected that GOs will need to modify any of these settings.

During normal operations the LECS will be switched off during:

- South Atlantic Anomaly Passages
- Bright Earth Transits

The latter is necessary to avoid the possibility of damaging the PMT due to too high levels of incident light.

4.3.8 Data Configuration

The LECS flight software produces three types of telemetry data products: Science data, Housekeeping, and Engineering Housekeeping. The formats of the HK and Engineering HK data are fixed, while the science data mode can be selected according to the scientific priorities and Telemetry limitations of a particular observation.

4.3.8.1 Science Data Modes

The nominal science transmission mode of the LECS is DIRECT. The default mode is DIRECT configured to provide 16 μ sec time resolution. If a target produces too much telemetry in this configuration (see below), then 1 second time resolution can be selected. Each DIRECT mode event consists of:

Table 4.3-3. DIRECT Mode Contents

Item	Description	Bits
X	Event X co-ordinate (0-255)	8
Y	Event Y co-ordinate (0-255)	8
BL	Event burstlength (0-255)	8
Veto	Event veto value (0-255)	8
Time	Event time	6 or 22
E	Event energy (0-1023)	10

As well as the event data, each DIRECT mode packet contains a header with information on any selection criteria applied to the data.

The names to be specified in the instrument form as described in the SAO1 are LE_DIR_FTP for the 16 μ sec time resolution DIRECT mode(the default) or LE_DIR_CTP for the 1 sec time resolution direct mode.

Two other modes, SPECTRUM and IMAGE are available, but are not supported for GO's. As their names suggest, they can be used to accumulate on-board spectra and images in order to reduce the telemetry allocation for the LECS. However, given the complex interaction between the incident X-rays and the LECS window support structure (see Figure 4.3-10), their usage should only be considered if there are no other ways of reducing the overall telemetry load.

4.3.8.2 HK Data Contents

LECS HK telemetry consists of pressures, temperatures, voltages, status words and ratemeter data that is placed into telemetry every 1, 4, or 16 sec depending on the parameter. The data format is fixed and a HK packet is placed into telemetry every 1 sec.

4.3.8.3 Engineering HK Contents

Engineering HK data consists of the last "snapshot" of normal HK data, error reporting and a dump of part of the LECS memory. One fixed format packet is placed into telemetry every 10 sec.

4.3.8.4 Telemetry Limitations

The telemetry requirements of the individual SAX instruments have to be balanced within the overall allocation (see section 4.9).

Table 4.3-4 lists the components of the LECS science telemetry and their required Telemetry. The amount of source telemetry required can be calculated by noting that each event takes 64 bits if 16 μ sec time resolution is required, or 48 bits if 1 sec time resolution is sufficient.

Table 4.3-4 LECS Telemetry Requirements

Component	Telemetry	Telemetry	Comment
	(kbits/sec)	(kbits/sec)	
	T = 1 sec	T = 16 μ sec	
X-ray Source	48 bits/event	64 bits/event	
Engineering HK	0.9	0.9	Constant, 1 Packet /10 sec
Calibration Sources	2.1	2.8	40 Counts/sec
Background	0.2	0.2	3 Counts/sec

Figure Captions

Figure 4.3-1. Schematic of the LEGSPC Instrument

Figure 4.3-2. A schematic of the LEGSPC Detector Unit

Figure 4.3-3. Plasma Protection Window Cross-section

Figure 4.3-4. Entrance Window Cross-section

Figure 4.3-5. Window Support Grid Structure.

Figure 4.3-6. Window Support Strongback Structure.

Figure 4.3-8. An LECS image of a multi-pinhole array.

Figure 4.3-9. The Overall On-Axis Efficiency of the LECS.

Figure 4.3-10. A scan along the Y axis of the window showing the obscuration caused by the window support mechanism.

Figure 4.3.11. LECS Window Measurement Positions

Figure 4.3-12. The response of the LECS to 0.28 and 8.04 keV monochromatic X-rays.

Figure 4.3-13. SAX LECS 5σ Minimum Detectable Source Count Rates

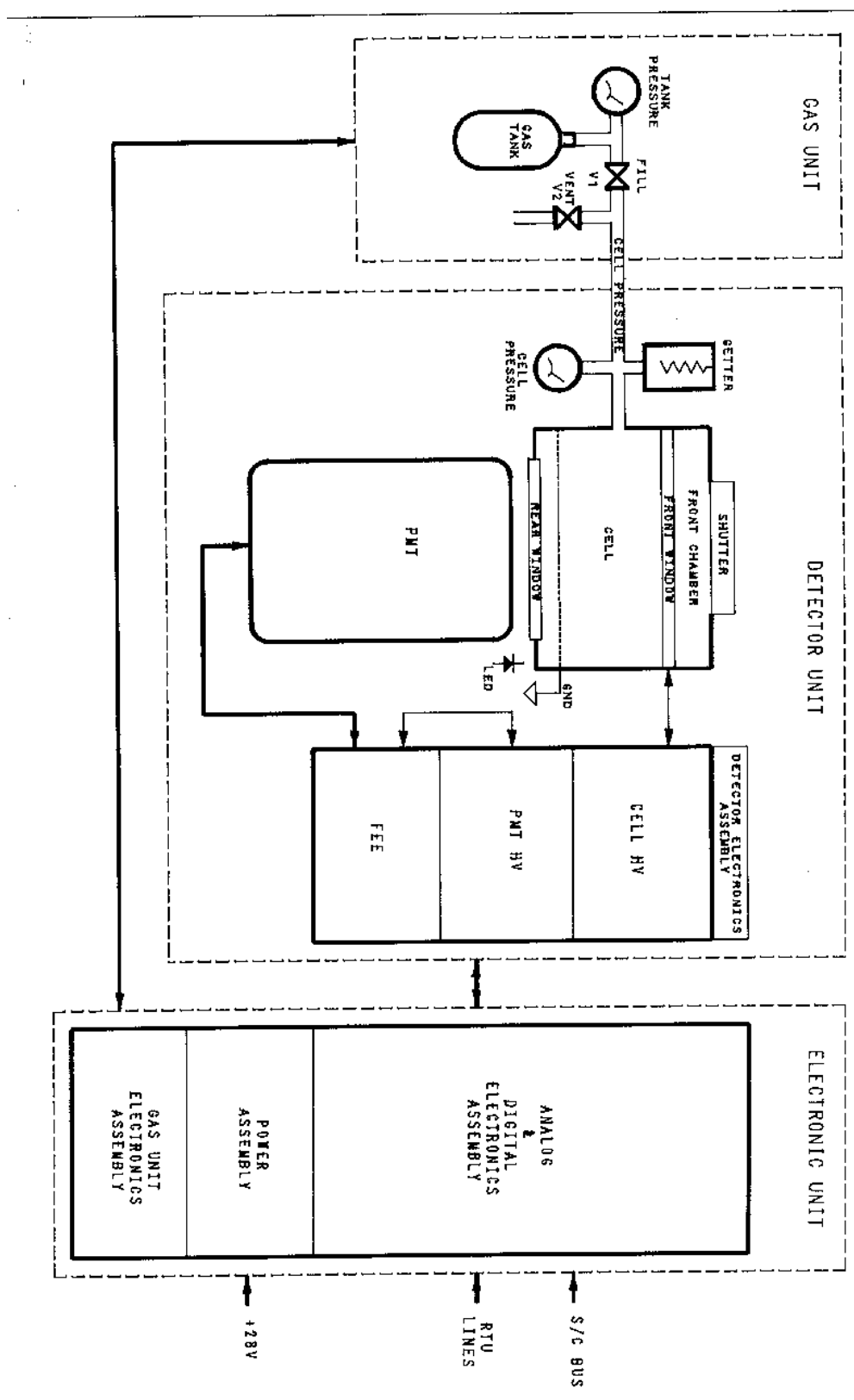
Figure 4.3-14 and 4.3-15. LECS Power-law Conversion Factors

Figures 4.3-16 and 4.3-17. Thermal Line Conversion Factors

Figures 4.3-18 and 4.3-19. Blackbody Conversion Factors.

Figures 4.3-20 and 4.3-21. LECS Line Sensitivity

Figure 4.3-22 LECS Sensitivity to Source Variability.



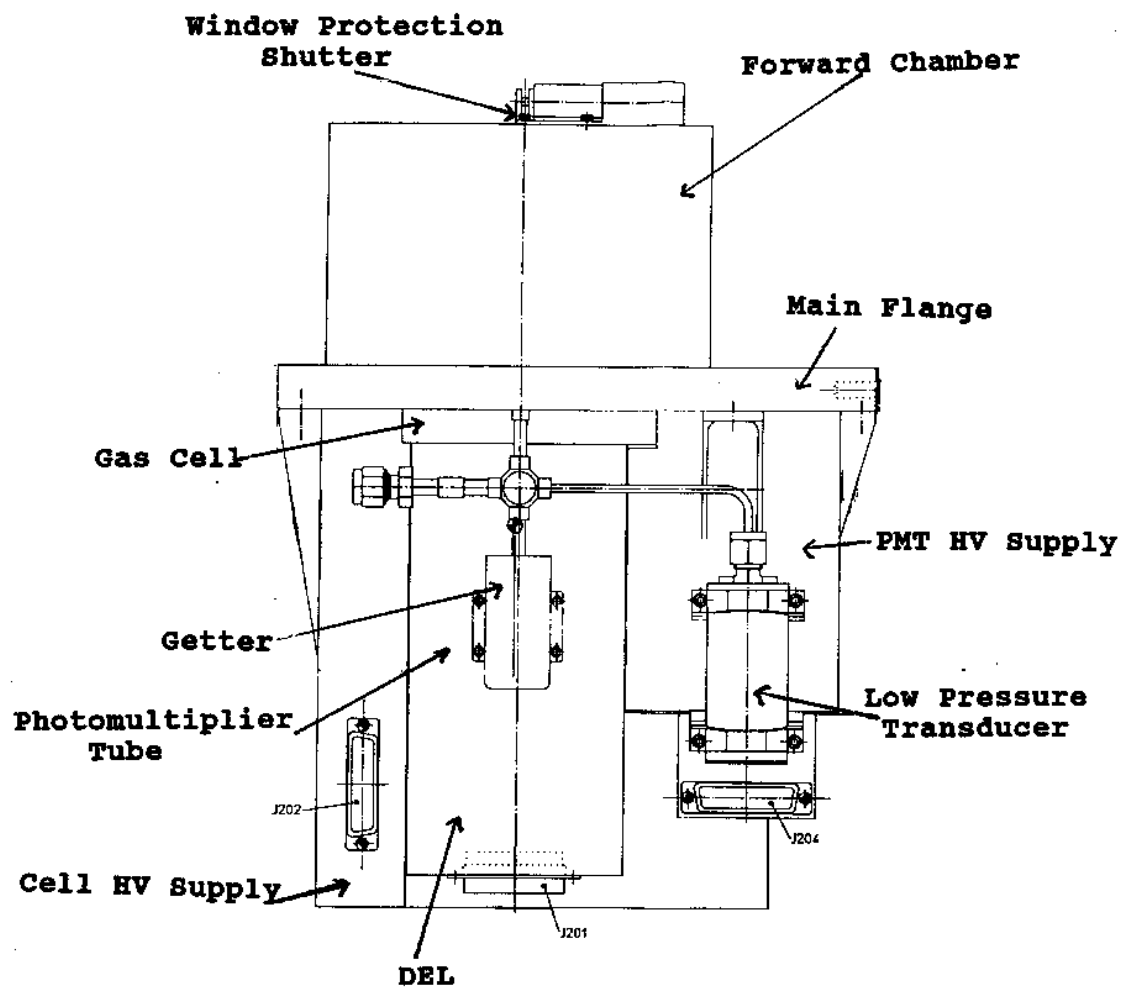
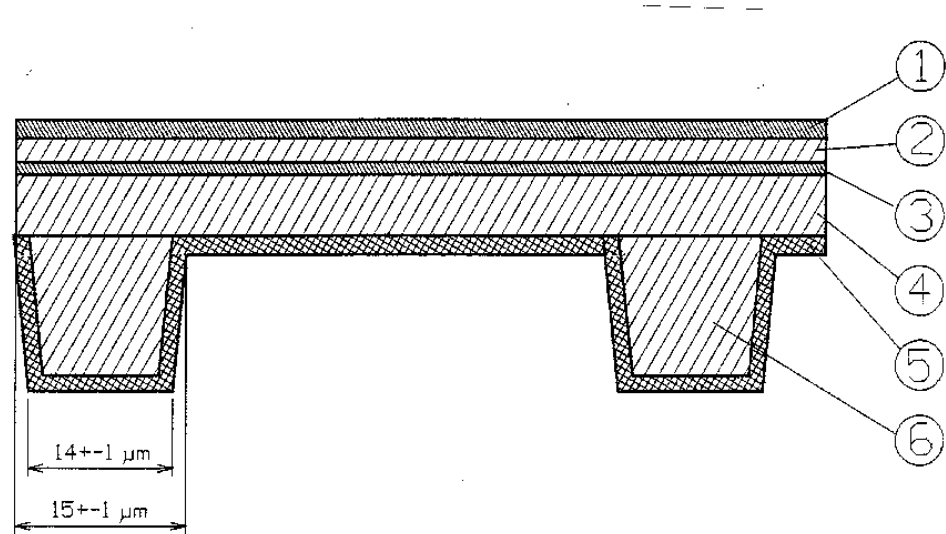


Fig.4.3.2



1	AlN, substoichiometric	20+-2 nm
2	Polyimide	39+-8 nm
3	AlN, nearly stoichiometric	10+-1 nm
4	Polyimide	161+-13 nm
5	Carbon (partly DLC)	20+-2 nm
6	Polyimide grid, 250 μm pitch	16.5+-1.5 μm
Note: layer 2 for the DM/QM:s		32+-10 nm

Fig.4.3.3

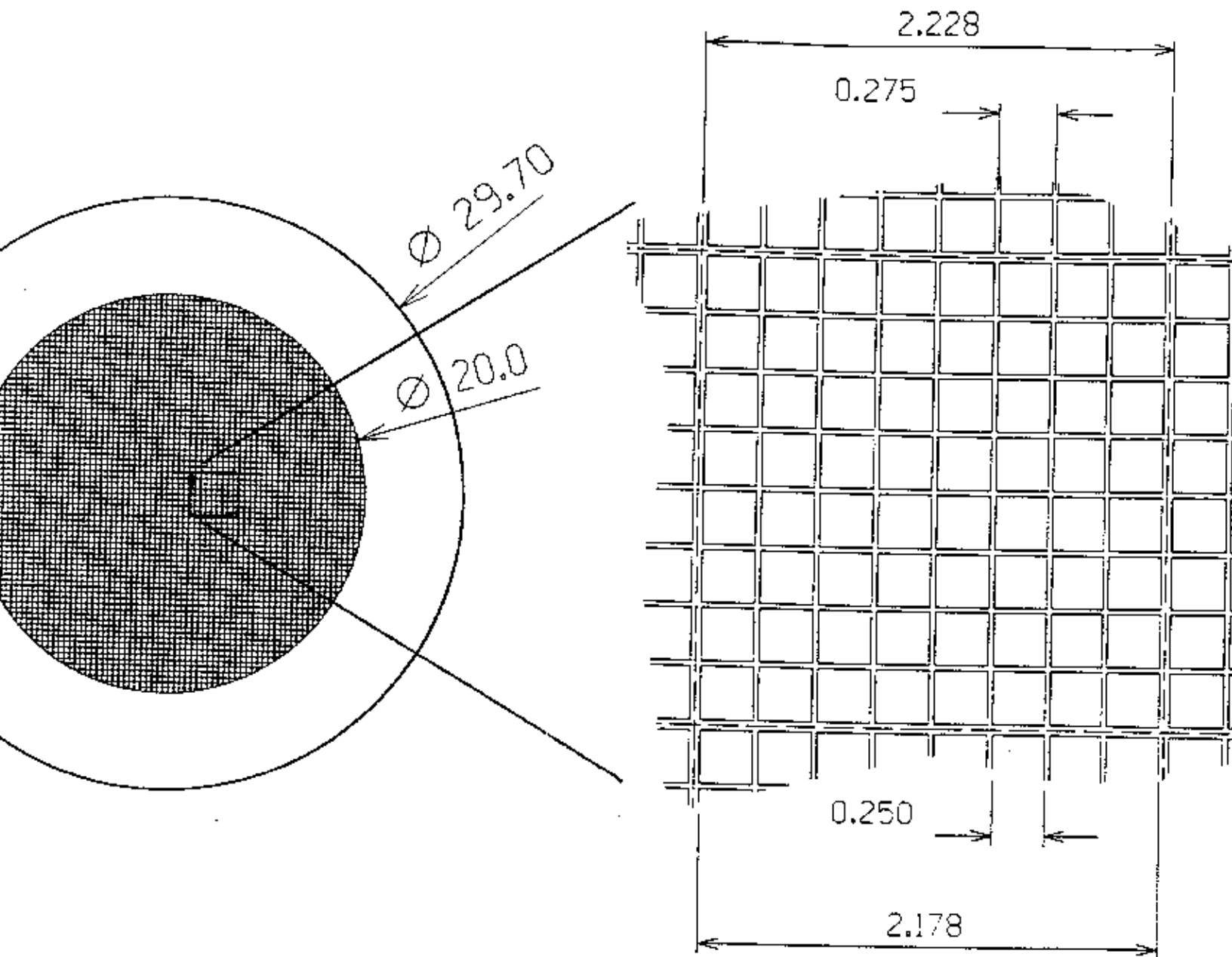


Fig.4.3.5

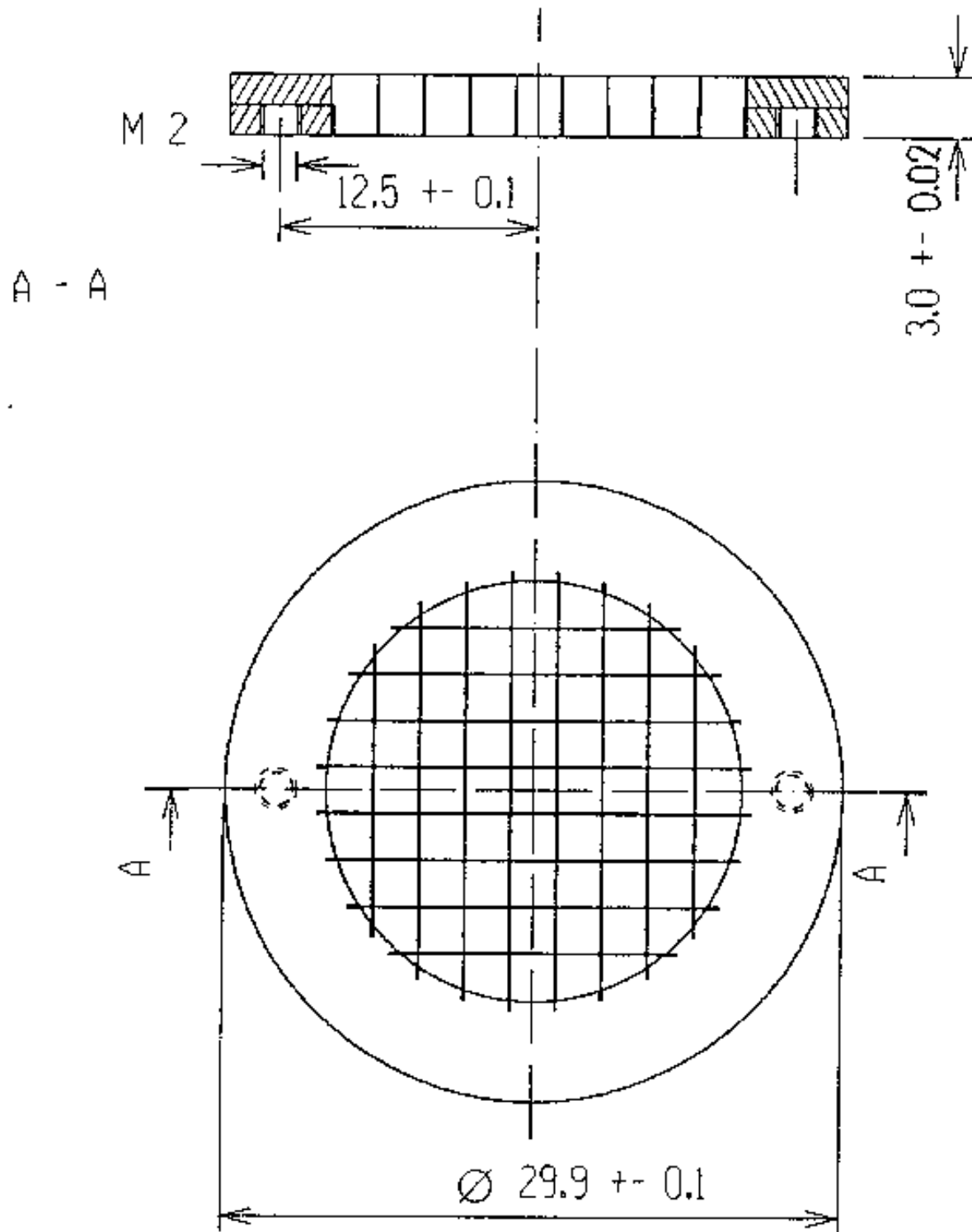


Fig. 4.3.6

Fig.4.3.8

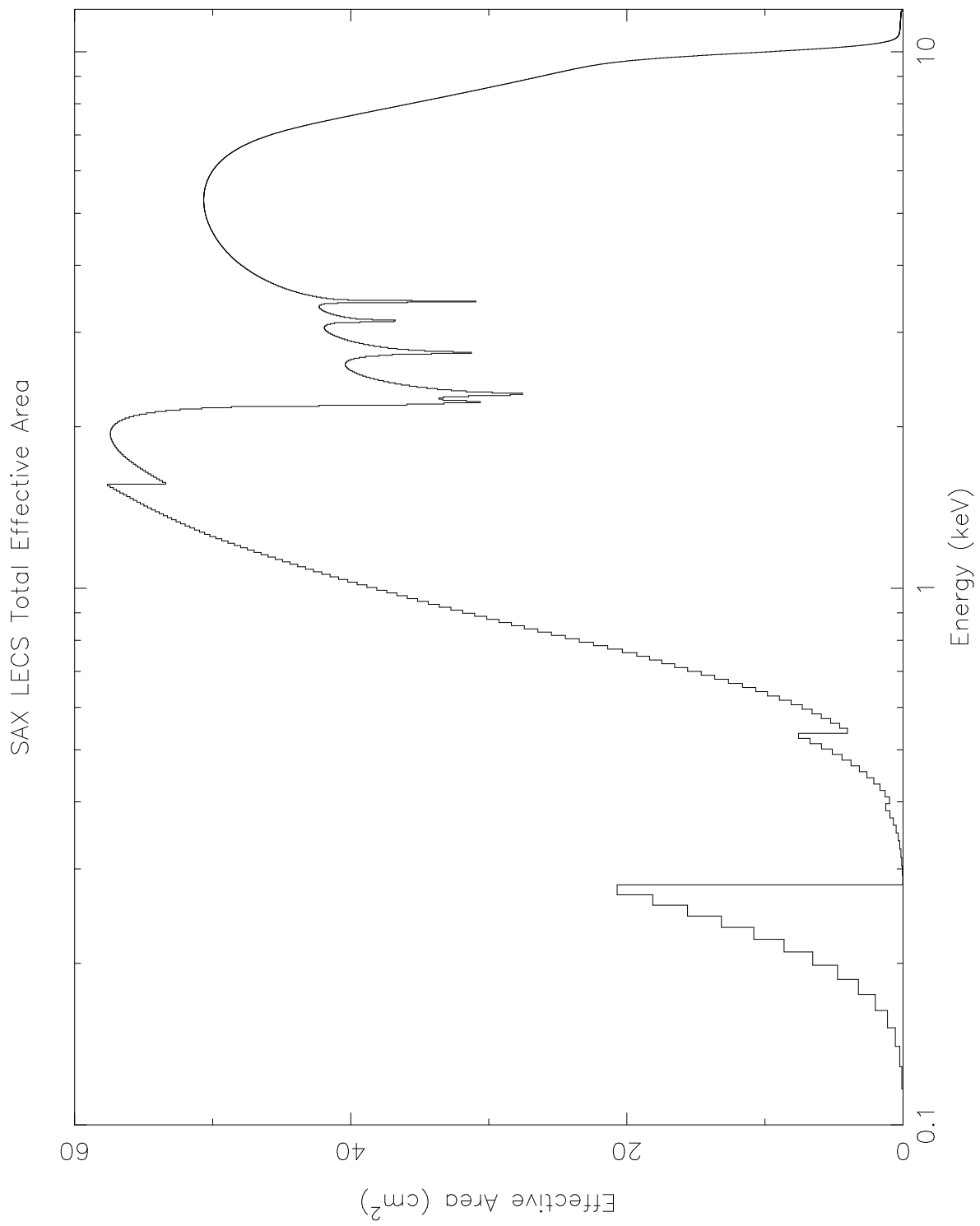


Fig.4.3.9

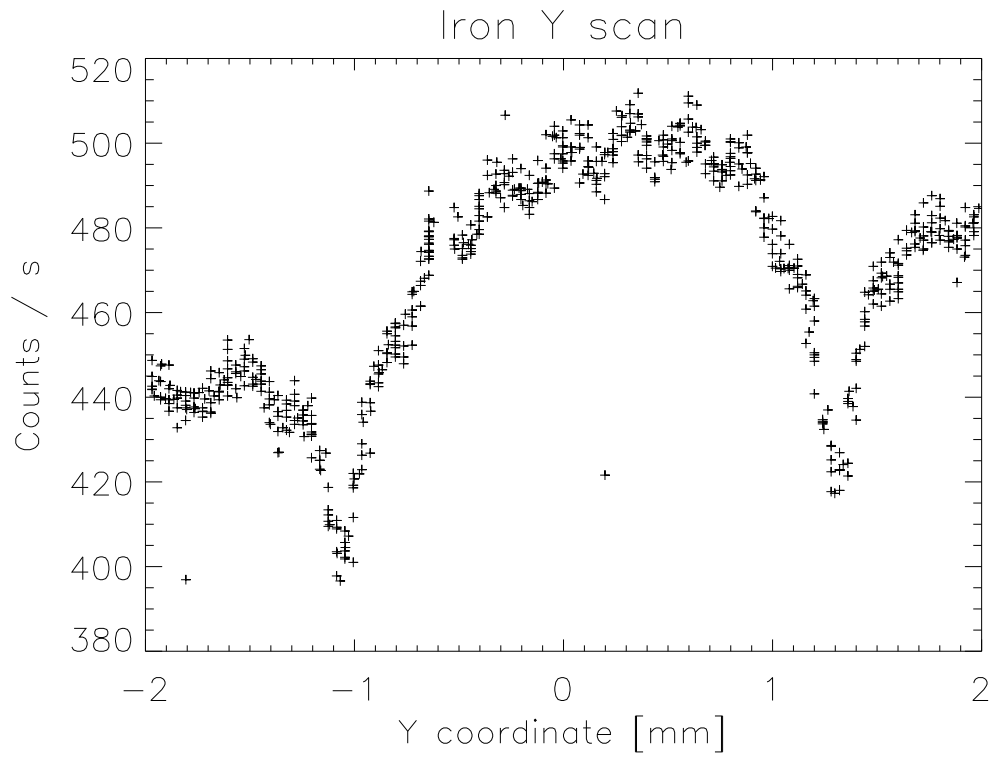


Fig. 4.3-10

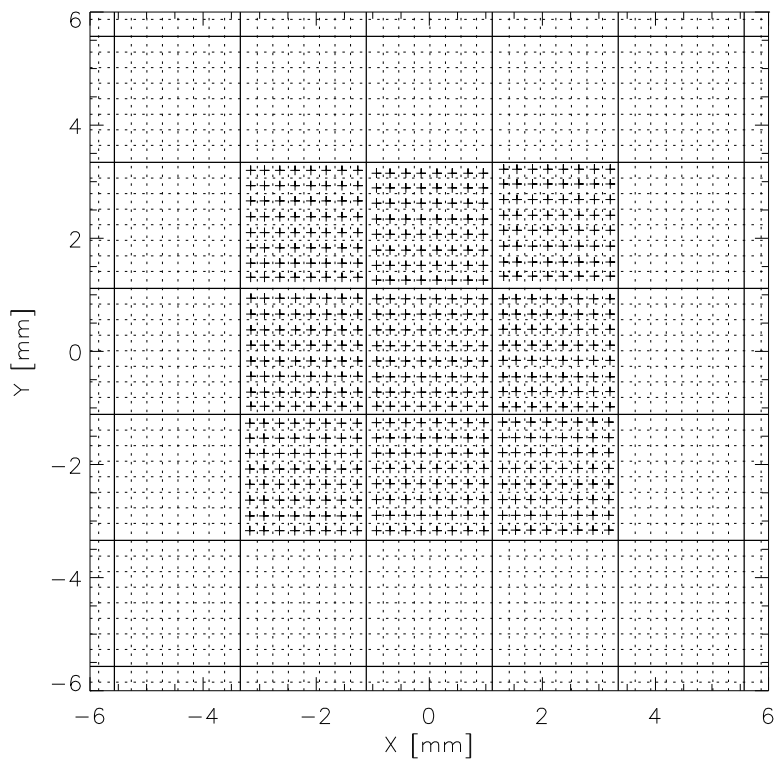


Fig. 4.3.11

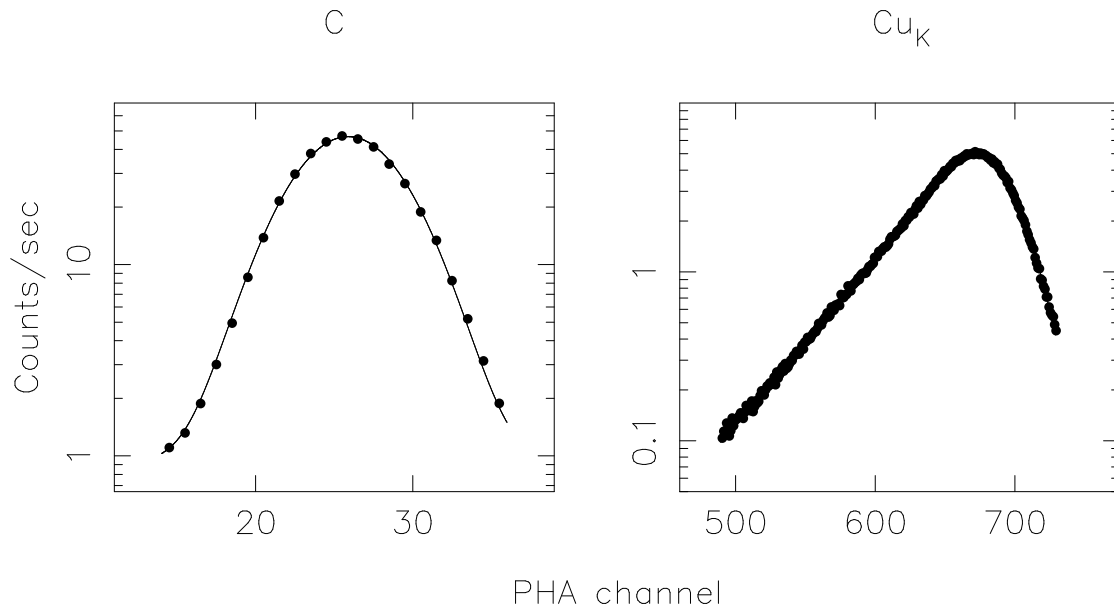


Fig. 4.3.12

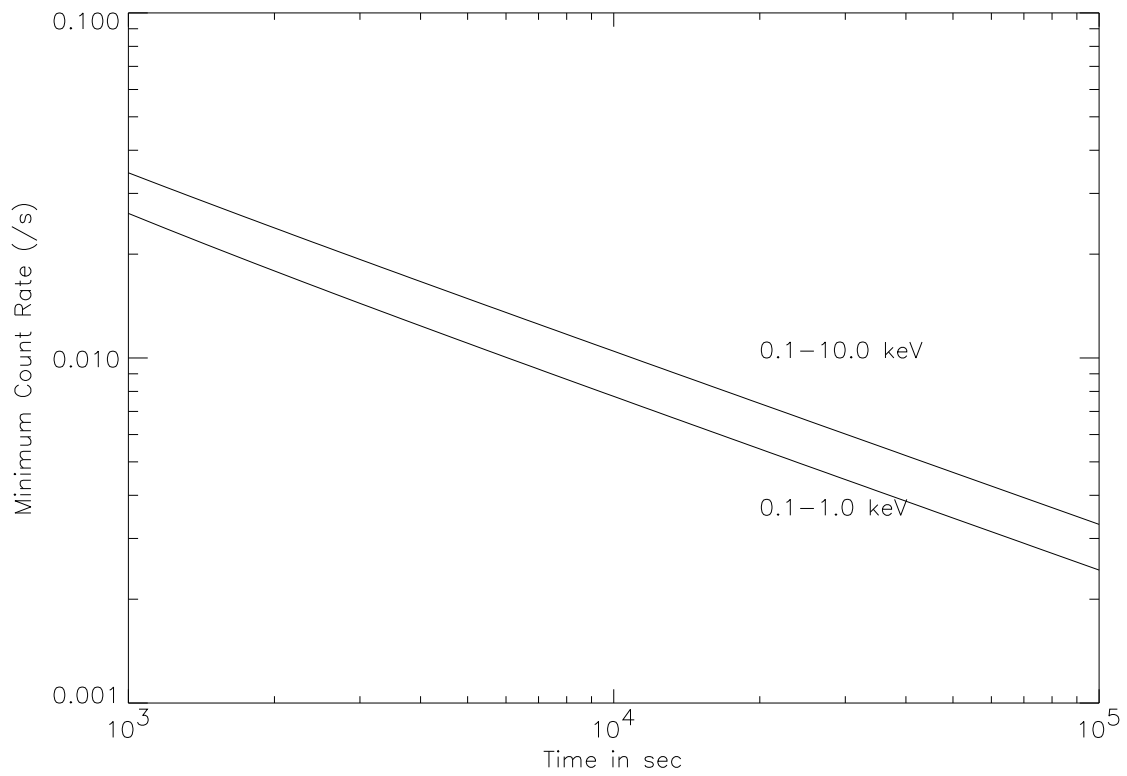


Fig.4.3.13

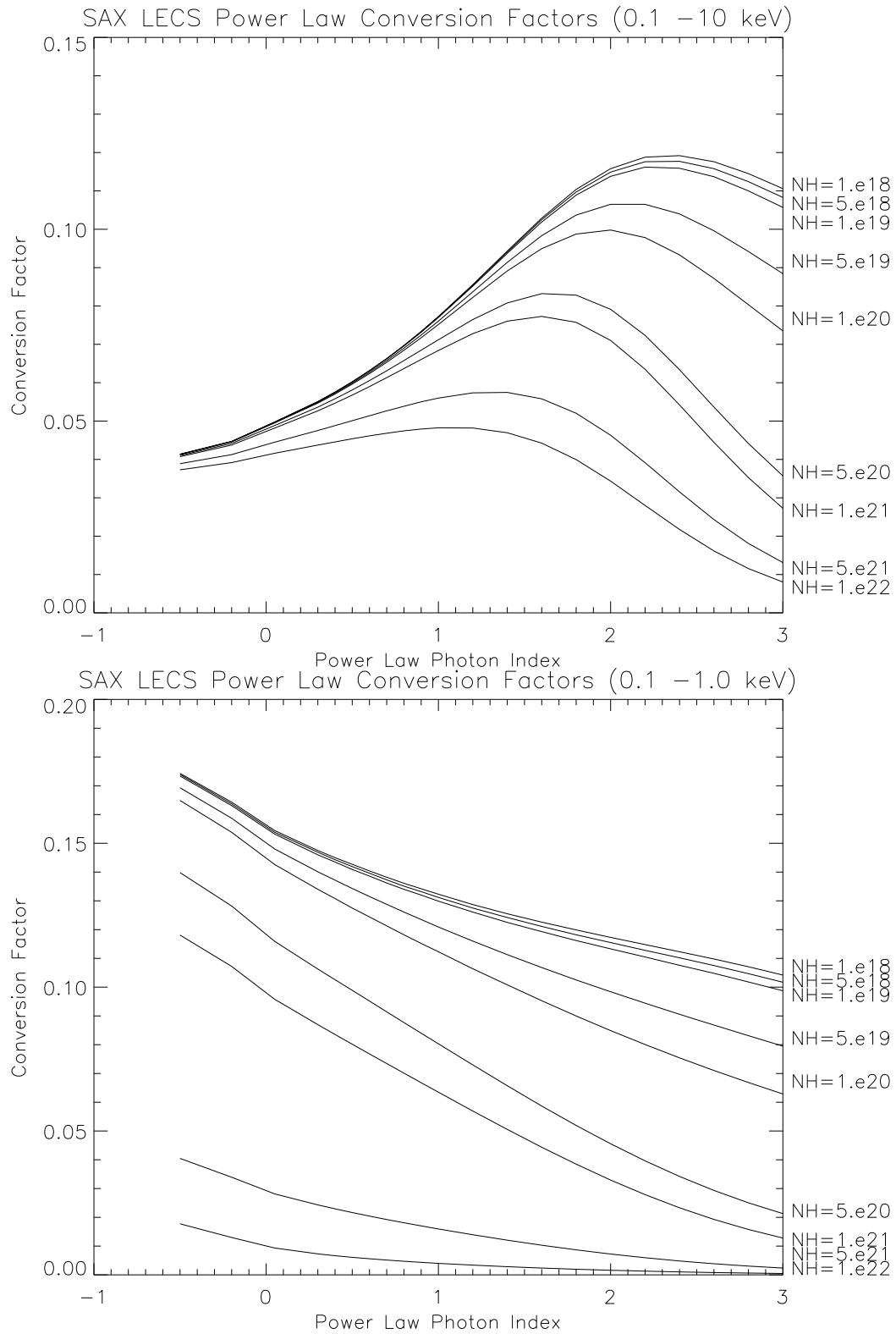


Fig 4.3.14 and 4.3.15

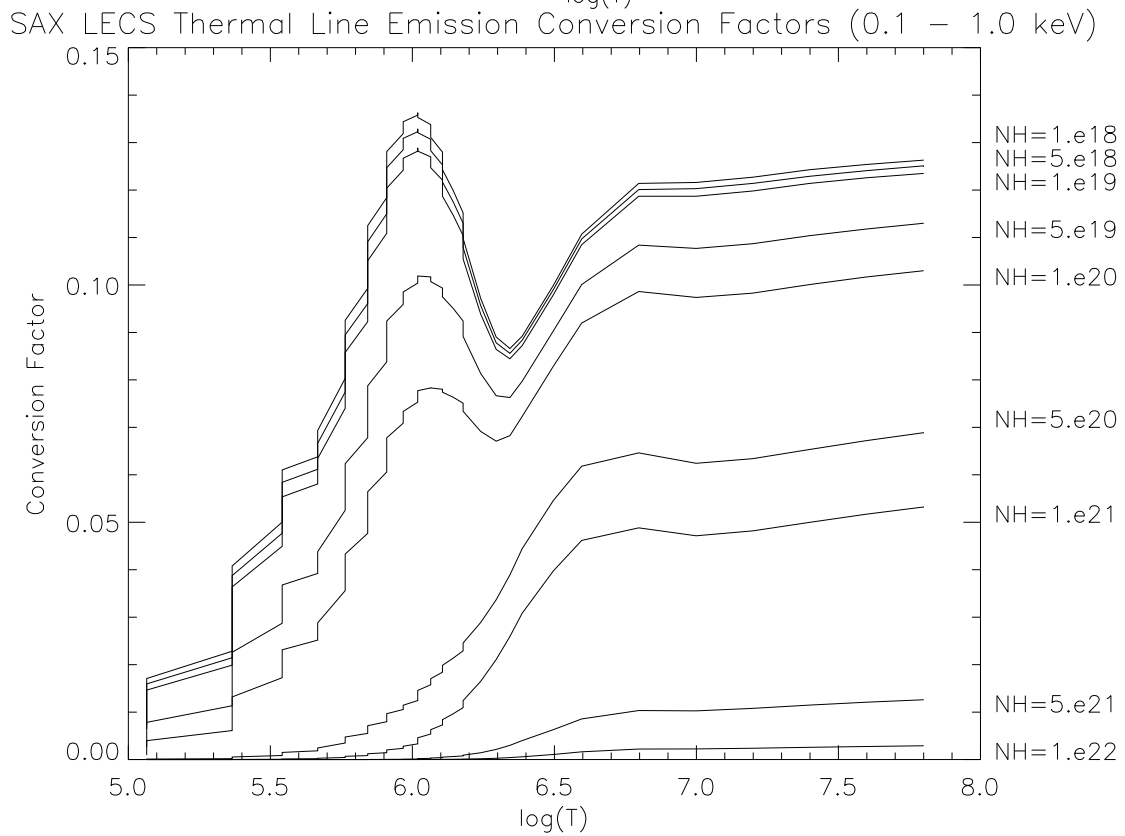
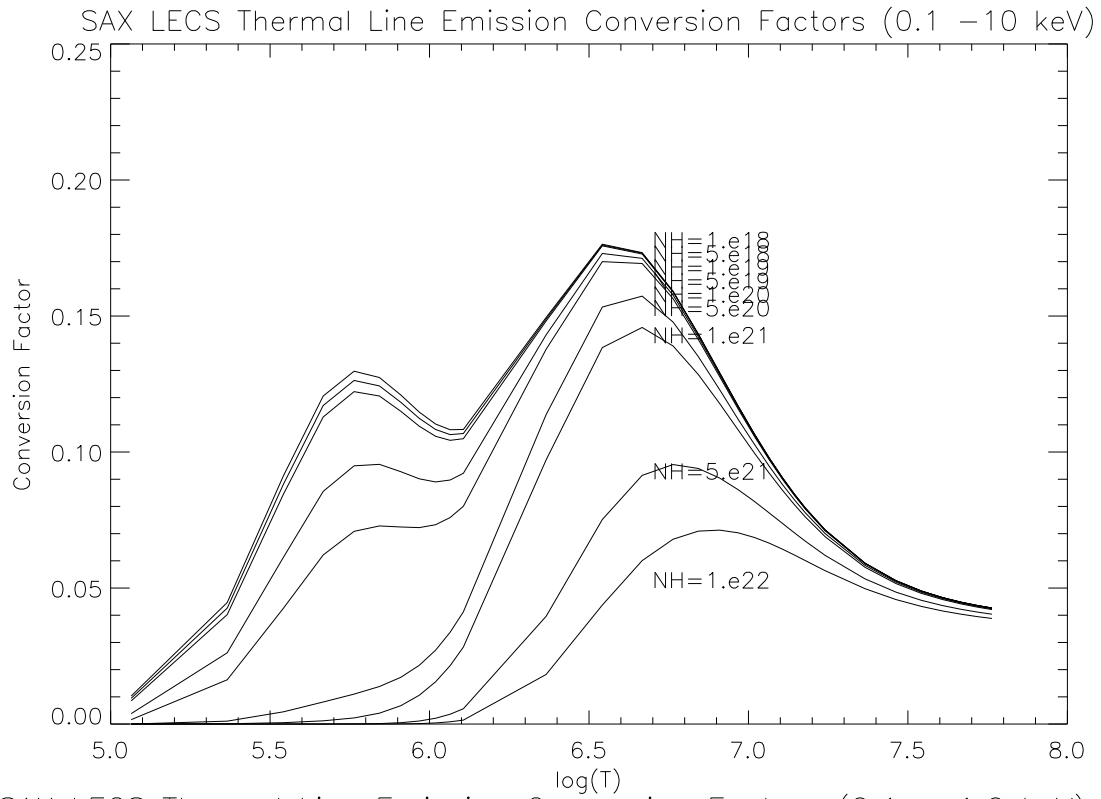


Fig.4.3.16 and 4.3.17

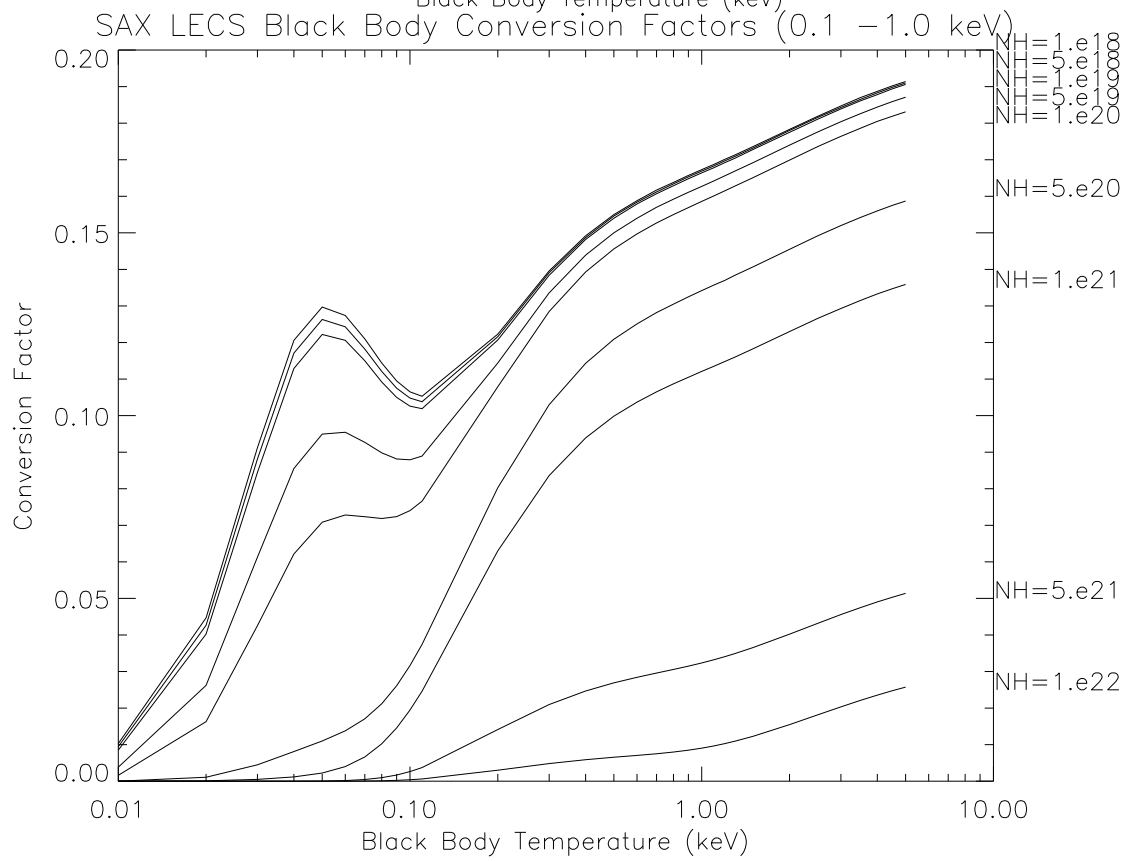
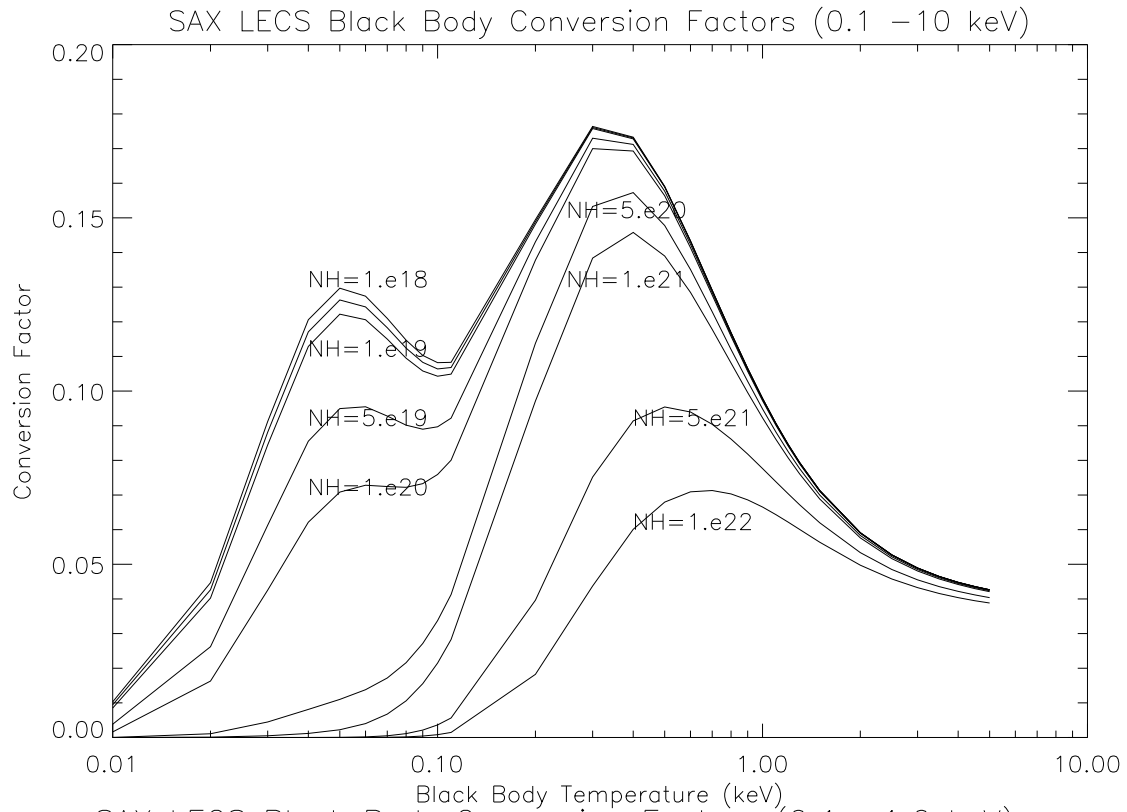


Fig 4.3.18 and 4.3.19

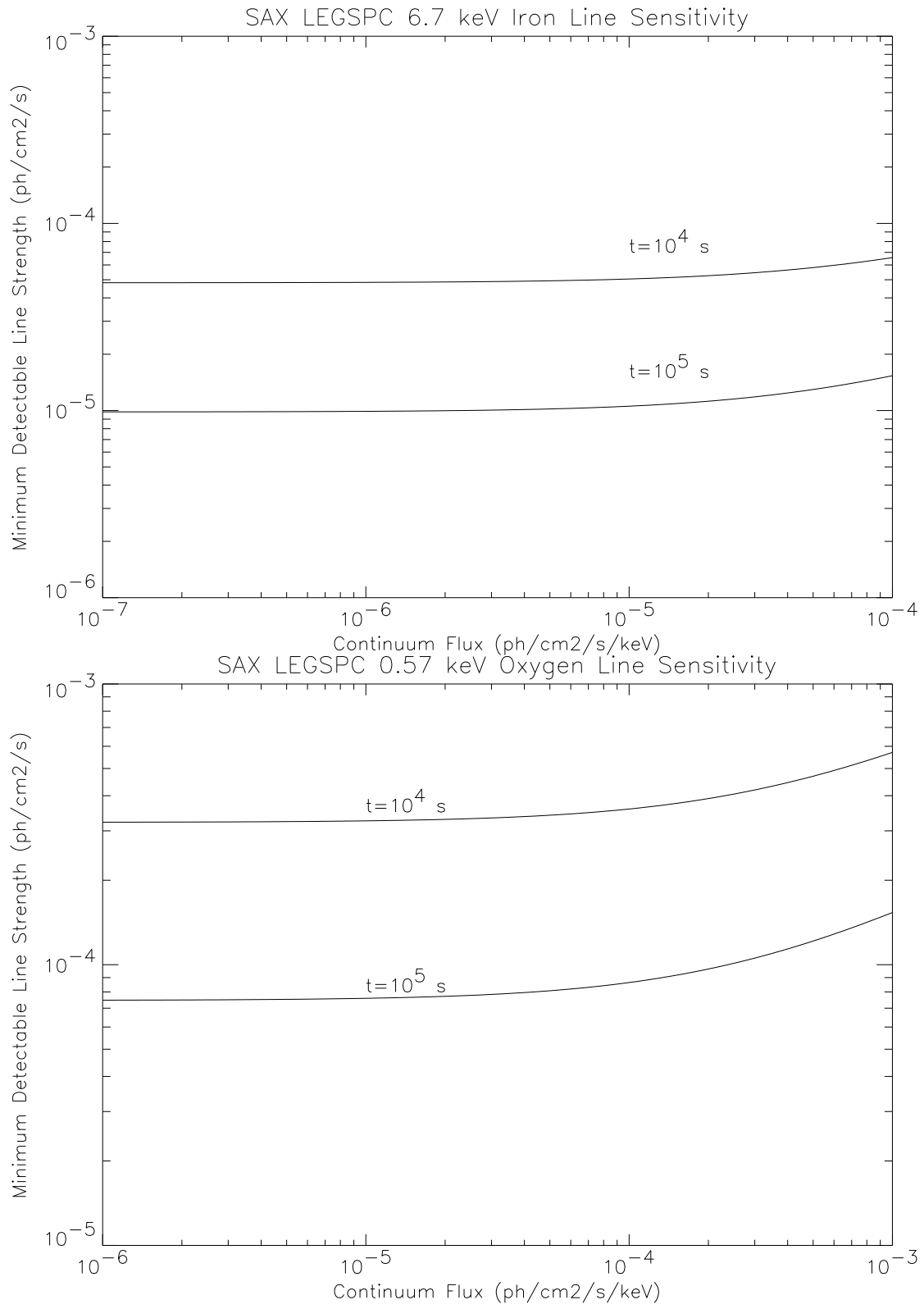


Fig. 4.3.20 and 4.3.21

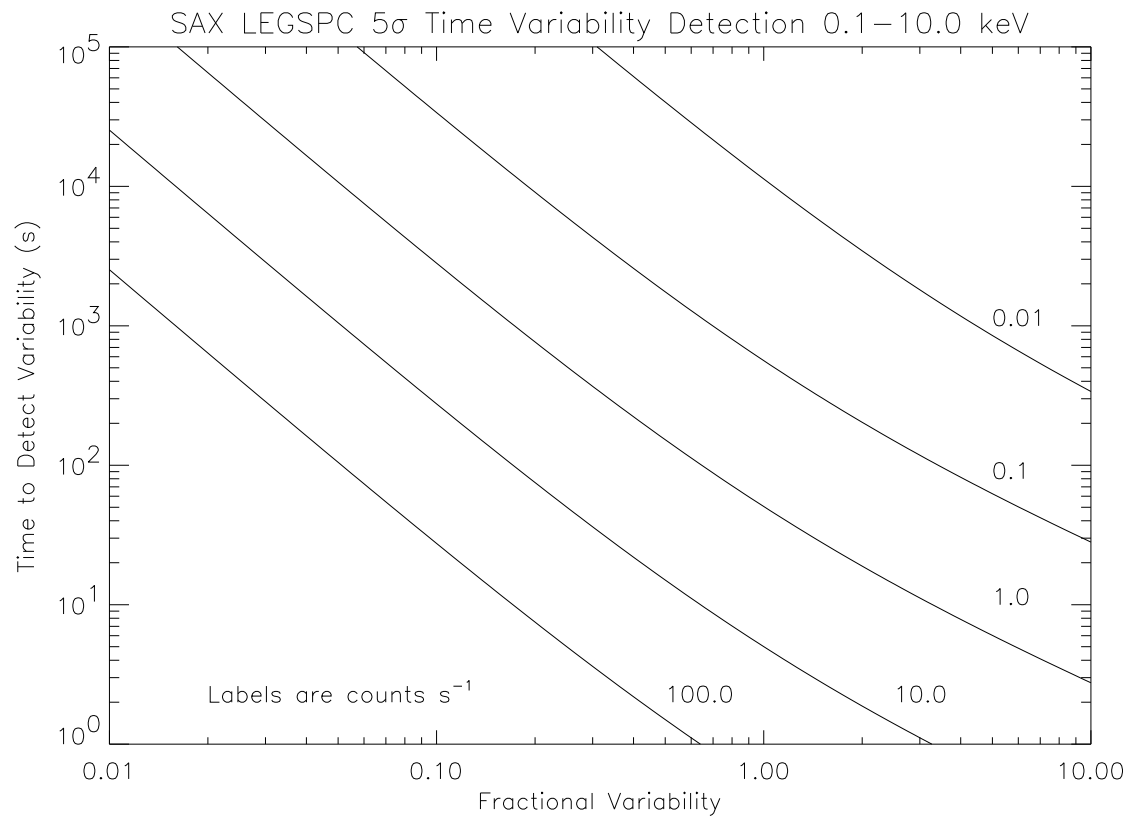


Fig. 4.3.22

4.4. MECS³

4.4.1. Introduction

The MECS (Medium Energy Concentrator Spectrometer) instrument consists of three identical units designed to enhance the X-ray sensitivity above 1.0 keV. The optical system of each unit has been previously described in paragraph 4.2.. The focal plane detectors, three gas scintillation proportional counters, (MEGSPC) are sensitive in the range 1.3 - 10.0 keV with a circular FOV of 30° arcminute radius. A schematic of the X-ray entrance window is reported in figure 4.4.1.

The detectors exploit the UV light produced in a high electrical field region to which the electron cloud, resulting from the X-ray photo absorption, is drifted from the absorption region. The amplitude of the UV signal, detected by a position sensitive photomultiplier, is proportional to the energy of the absorbed X-ray. The duration of the signal, the so called Burst Length (BL), is used to discriminate genuine X-rays against induced background events.

Two Fe⁵⁵ calibration sources, continuously visible just at the edge of the FOV, allow an absolute calibration and monitoring of the gain of the detector.

4.4.2. Performance

The overall characteristics of the MECS instrument are reported in Table 1, key parameters of the focal plane detectors are listed in Table 2. The angular resolution of the instrument is limited at low energies by the position capabilities of the detectors and at high energies by the point spread function of the optics.

4.4.2.1. Quantum efficiency

Quantum efficiency of the MECS instrument is limited at low energies by the thickness of the Beryllium window of the focal plane detectors and at high energies by the loss of reflectivity of the mirrors. Figure 4.4.2 shows the effective collecting area as function of the energy for different off axis angles.

³Contribution By S. Re, B.Sacco, T. Mineo

Table 1: MECS Instrument characteristics

Field of view	30' radius
Angular resolution	at 1.5 keV: 105", 165"
(radius containing 50% and 80%)	at 6.4 keV: 75", 150"
	at 8.1 keV: 75", 150"
Energy range	1.3 -10.0 keV
Energy resolution (% FWHM)	$8*(E/6)^{-0.5}$
Effective on axis collecting area	at 1.5 keV: 39 cm ²
	at 6.4 keV: 148 cm ²
	at 8.1 keV: 97 cm ²
Time resolution	15 μ s
Maximum throughput	2000 cts/sec
Image binning	256 x 256 pixels
Image pixel dimension	20" (square)
Energy binning	256 channels
Burst length binning	256 channels

Table 2: Focal plane detector

Gas Type	Xenon
Gas filling pressure	1.0 atm at 25° C
X-ray window:	
material	Beryllium
diameter	30.0 mm
thickness	50 μ m
support frame material	Be
" thickness	0.35 mm
central region diameter	9.0 mm = 16.5 arcmin
Position resolution (HPR)	$0.7*(E/6)^{-0.5}$ arcmin

4.4.2.2. Energy resolution and linearity

The energy resolution and linearity of the MEGSPC have been measured over the full energy range and over the full sensitive area. The resolution can be well approximated, over the full area, by the relation:

$$\Delta E/E = 8 * (E/6)^{-0.5} \text{ FWHM } \%$$

Energy information slightly depends on position, and have to be corrected on ground. Indirect observation modes (energy spectra) may be applicable only for point-like sources after in flight tests. They are not currently supported.

A gain jump at the L edge of the Xenon has been previously measured for this kind of detector. The jump (+140 eV) is the cause for a "bump" at 4.7 keV. This effect is taken into account in the instrument response matrix.

4.4.2.3. Gain monitoring

Two calibration sources are continuously visible at the edge of the FOV and can be used to monitor the detector+photomultiplier gain and to calibrate the energy response at 5.9 keV (Fe⁵⁵ line).

4.4.2.4. Position resolution and linearity

The position resolution results from two effects: the detector and the optics response. The detector position resolution has been measured over the full window (30 mm diameter) and can be well approximated by:

$$\Delta P = 0.7 * (E/6)^{-0.5} \text{ arcmin HPR}$$

The optics point spread function has been treated in the optics paragraph (4.2). In table 1 we give the radii containing 80% and 50% of the counts for the combined optics + focal plane detector.

The position information has to be linearized for distortions in the photomultiplier detection system. The effect is negligible in the central 9 arcminutes of the FOV (central region of the Be window).

4.4.2.5. Background

The background of MECS is primarily due to particle induced X-rays and to diffuse extragalactic X-rays, the galactic component being practically not detected because of the thickness of the detectors' Beryllium window (less than 5% transparency below 1.0 keV).

Estimation from previously flown (EXOSAT) and currently in flight operating (ASCA) Gas Scintillation Proportional Counters brings to a conservative value of $2 \cdot 10^{-3} \text{ cts cm}^{-2}$

$\text{sec}^{-1} \text{keV}^{-1}$ ($=5.5 * 10^{-5} \text{ cts arcmin}^{-2} \text{ sec}^{-1}$) in the 2-10 keV band for the particle induced background, three times greater than that measured on ground.

From simulations, the expected count rate of the extragalactic component is $1.3 * 10^{-3} \text{ cts cm}^{-2} \text{ sec}^{-1} \text{ keV}^{-1}$ ($=3.5 * 10^{-5} \text{ cts arcmin}^{-2} \text{ sec}^{-1}$).

4.4.3. Instrument sensitivity

4.4.3.1. Minimum detectable count rate

The minimum detectable count rate depends on the background counting rate and on the size of the detection spot. Figure 4.4.3 shows the minimum observation time required for a significant detection. The detection criterion used is 10 photons for photon limited observations, and 5σ over the background for background limited observations. The fraction of signal collected in the detection spot (radius=2.5 arcmin) is fixed at 80%. The background count rate is computed considering both particle and diffuse components.

4.4.3.2. Minimum detectable Fe line strength

Figure 4.4.4 shows the sensitivity to 6.4 keV Fe line for observation times of 10^4 and 10^5 s. The detection criterion used is 10 photons for photon limited observations, and 5σ over the background continuum for background limited observations. The considered energy detection element is the FWHM and the detection spot is as before.

4.4.3.3. Count rate estimation

Expected MECS count rate depends strongly on the shape of the incident spectrum and on the absorption column density. Assuming as spectral model a power law or a black body or an optically thin thermal plasma function, the output count rate has been evaluated from the instrument simulator.

Figures 4.4.5, 4.4.6 and 4.4.7 show the energy to counts conversion factor. In order to obtain the expected on axis count rate, this factor has to be multiplied for the unabsorbed source flux in the energy range 1.0-10 keV in unit of $10^{-11} \text{ erg cm}^{-2} \text{ s}^{-1}$.

4.4.4. Data collecting modes supported for observers.

The MECS instrument can operate in two basic modes: *direct mode* in which basic

informations are telemetred for each detected event; *indirect mode* in which Burst Length (BL) and energy spectra are accumulated on board. Each mode has a set of submodes specified by the number of bits (or channels), time resolution and integration time.

The modes supported for observers are direct mode 2 and 3, differing for the time resolution (15 μ s for mode 2 and 16 ms for mode 3). Informations telemetred on ground for each mode are:

<i>ME_DIR2</i>		<i>ME_DIR3</i>	
Energy	8 bit	Energy	8 bit
BL	8 bit	BL	8 bit
X	8 bit	X	8 bit
Y	8 bit	Y	8 bit
T	24 bit	T	8 bit

Events are packed with the formats 215 events/pack (mode 3) and 154 events/pack (mode 2). Each packet requires 8912 bits equivalent to 41.45 bit per event (mode 3) and 57.87 bit per event (mode 2).

Calibration sources contribute with a count rate of 5 counts/seconds.

While running in direct mode, the instrument produces ratemeters source packets together with source data packets. Three ratemeters packets are completed in 60 seconds, generating a scientific telemetry of 445.6 bits/second.

Table 3 lists the components of the MECS science telemetry for the two modes.

In the proposal form, in the field Data Collection Mode (DCM) the user should specify ME_DIR2 for the mode with 15 usec resolution (the default) and ME_DIR3 for mode with 16 msec resolution

Table 3: MECS science telemetry

<i>Component</i>	<i>Telemetry (kbit/s)</i>	
	<i>ME_DIR2</i>	<i>ME_DIR3</i>
X-ray source (n cts/s)	0.058 * n	0.042 * n
Ratemeters	0.446	0.446
Calibration Sources (5 cts/s)	0.058 * 5	0.042 * 5
Particle Background (4 cts/s)	0.058 * 4	0.042 * 4
X-ray Background (0.2 cts/s)	0.058 * 0.2	0.042 * 0.2

Figure captions

Fig.4.4.1 Schematic of the focal plane detector entrance window

Fig.4.4.2 Effective collecting area as a function of energy for on-axis, 5', and 7.5' off-axis source positions

Fig.4.4.3 Minimum detectable source count rate vs. observation time

Fig.4.4.4 6.4 keV iron line sensitivity vs. continuum flux

Fig. 4.4.5 Flux to counts conversion factors for power law input spectrum as a function of the photon index

Fig. 4.4.6 Flux to counts conversion factors for blackbody input spectrum as a function of temperature

Fig. 4.4.7 Flux to counts conversion factors for optically thin thermal plasma input spectrum as a function of temperature

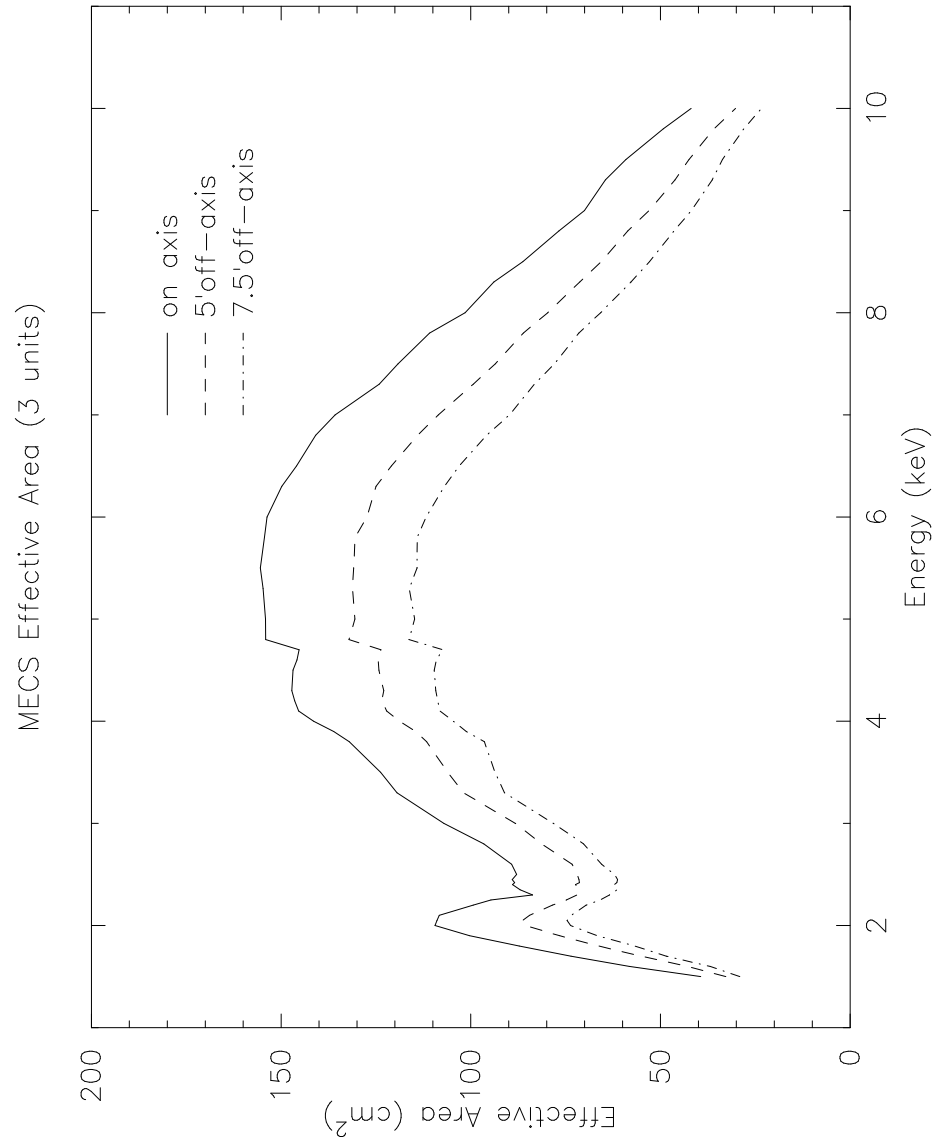
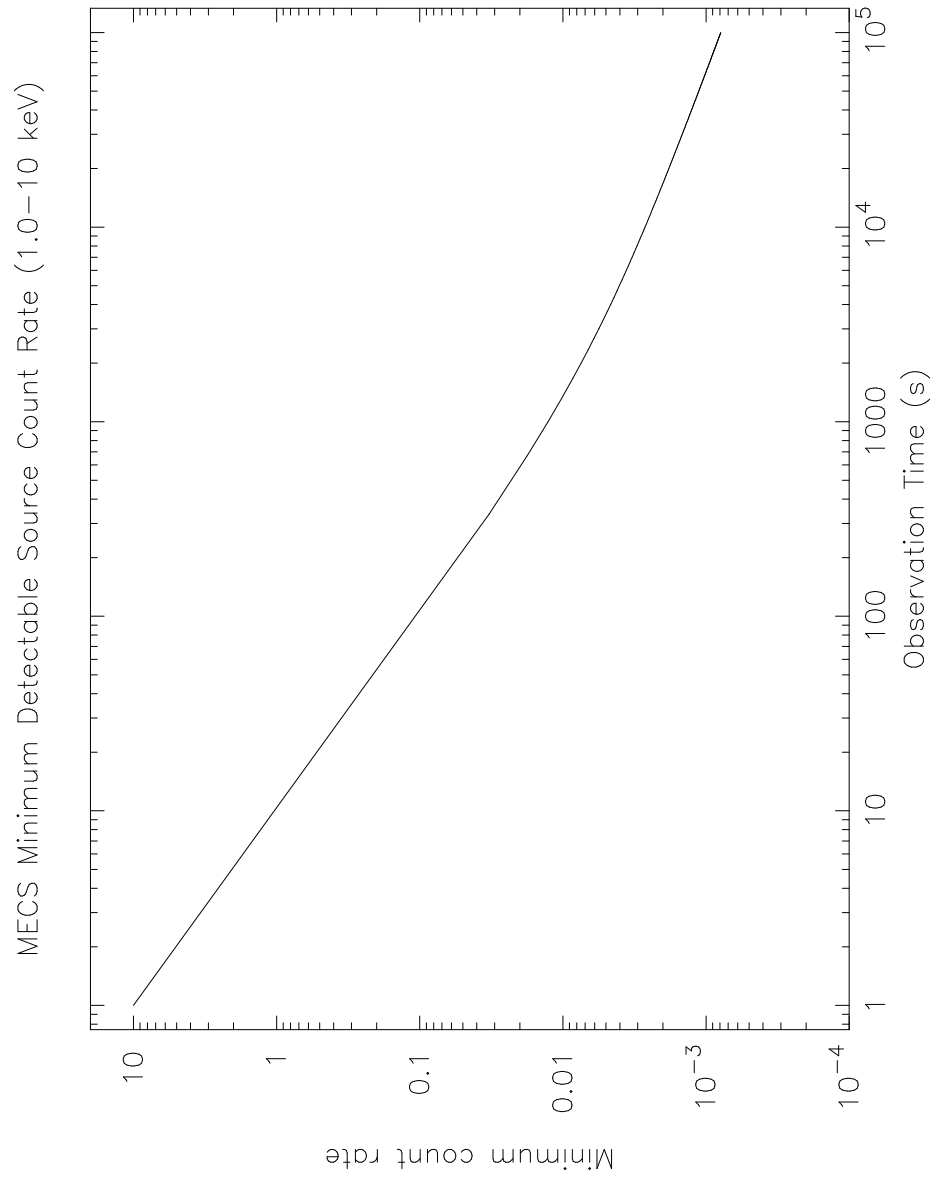


Fig.4.4.2

**Fig.4.4.3**

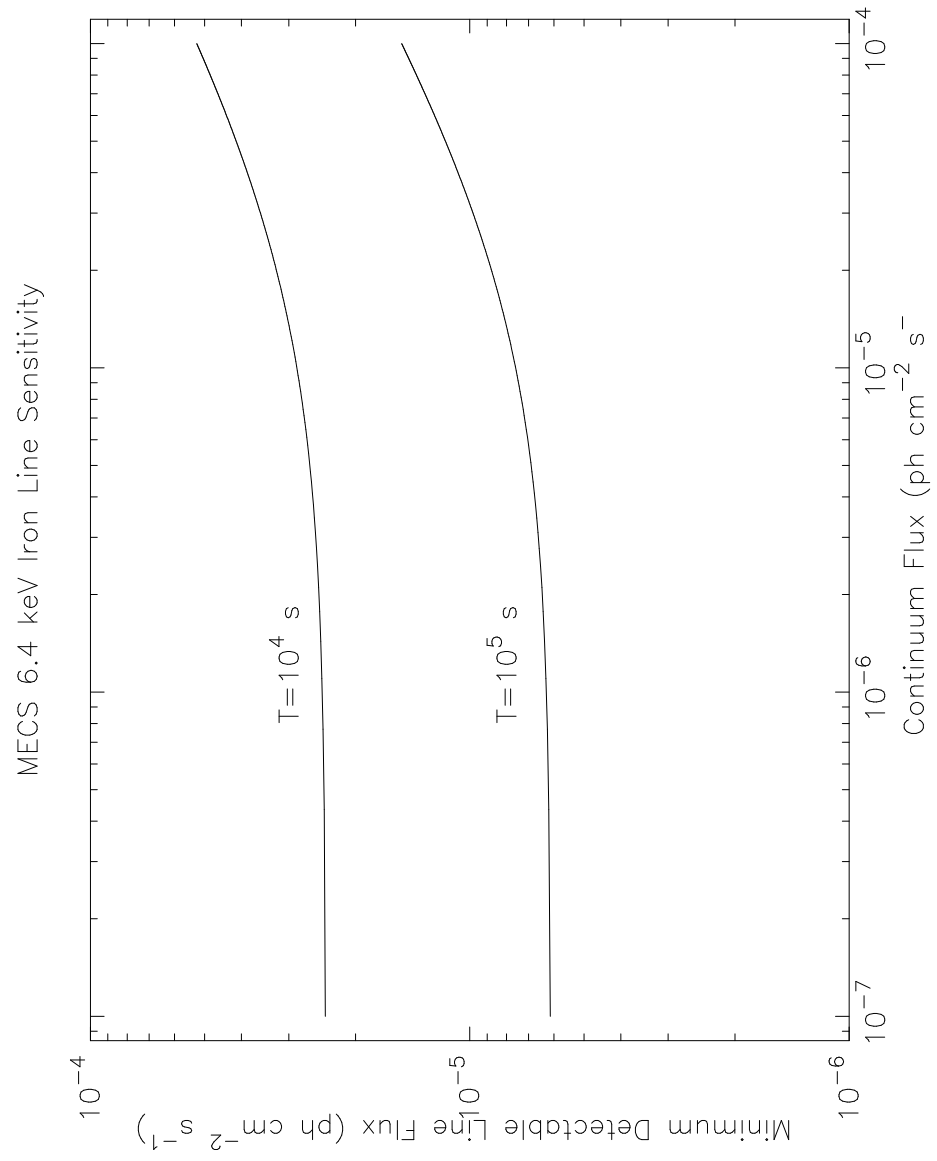


Fig.4.4.4

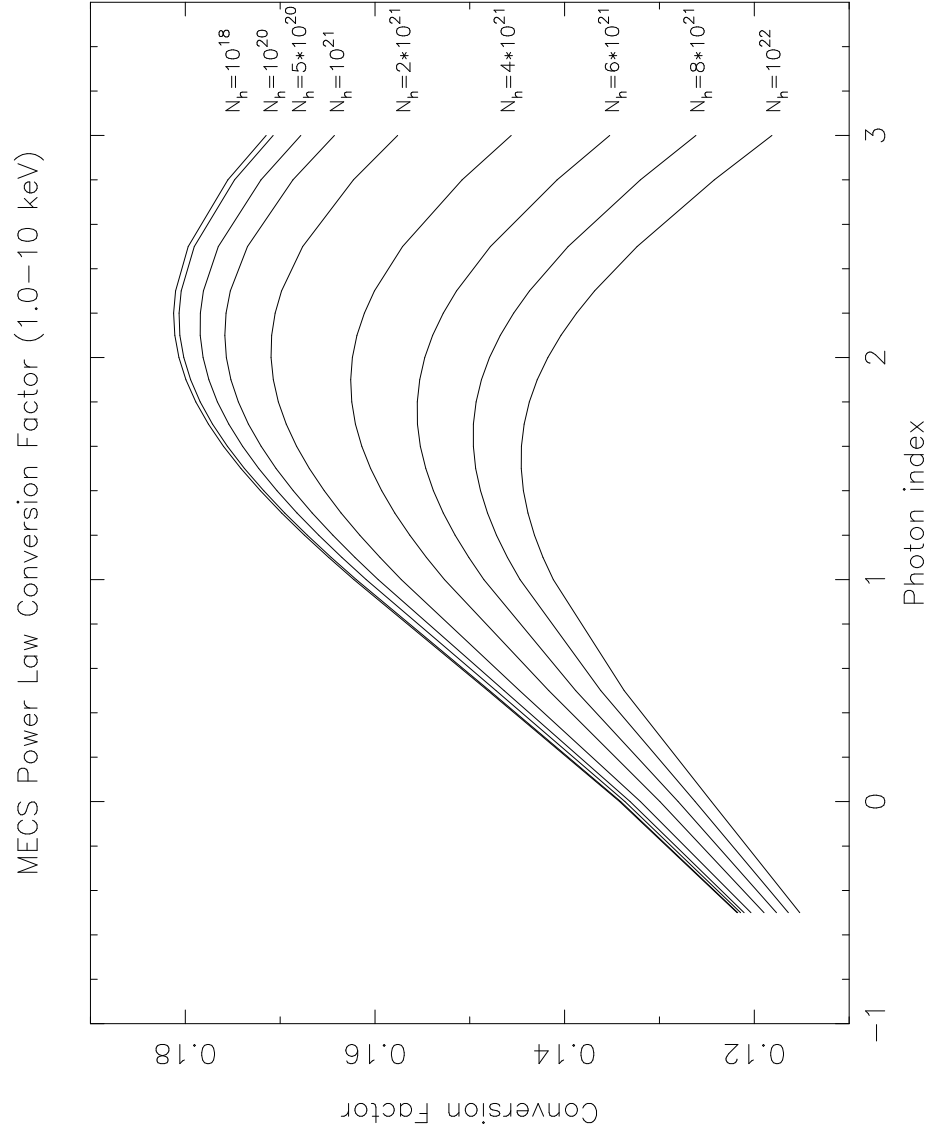


Fig.4.4.5

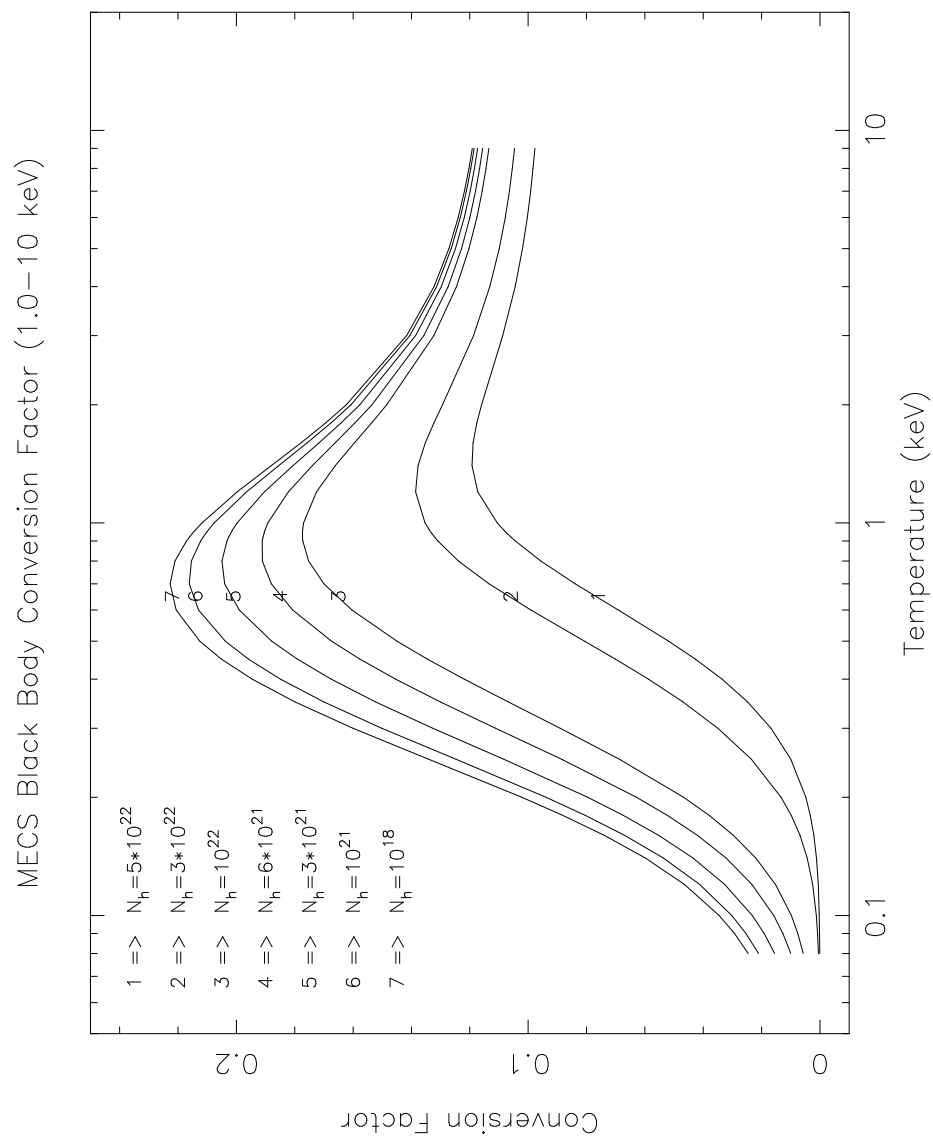


Fig.4.4.6

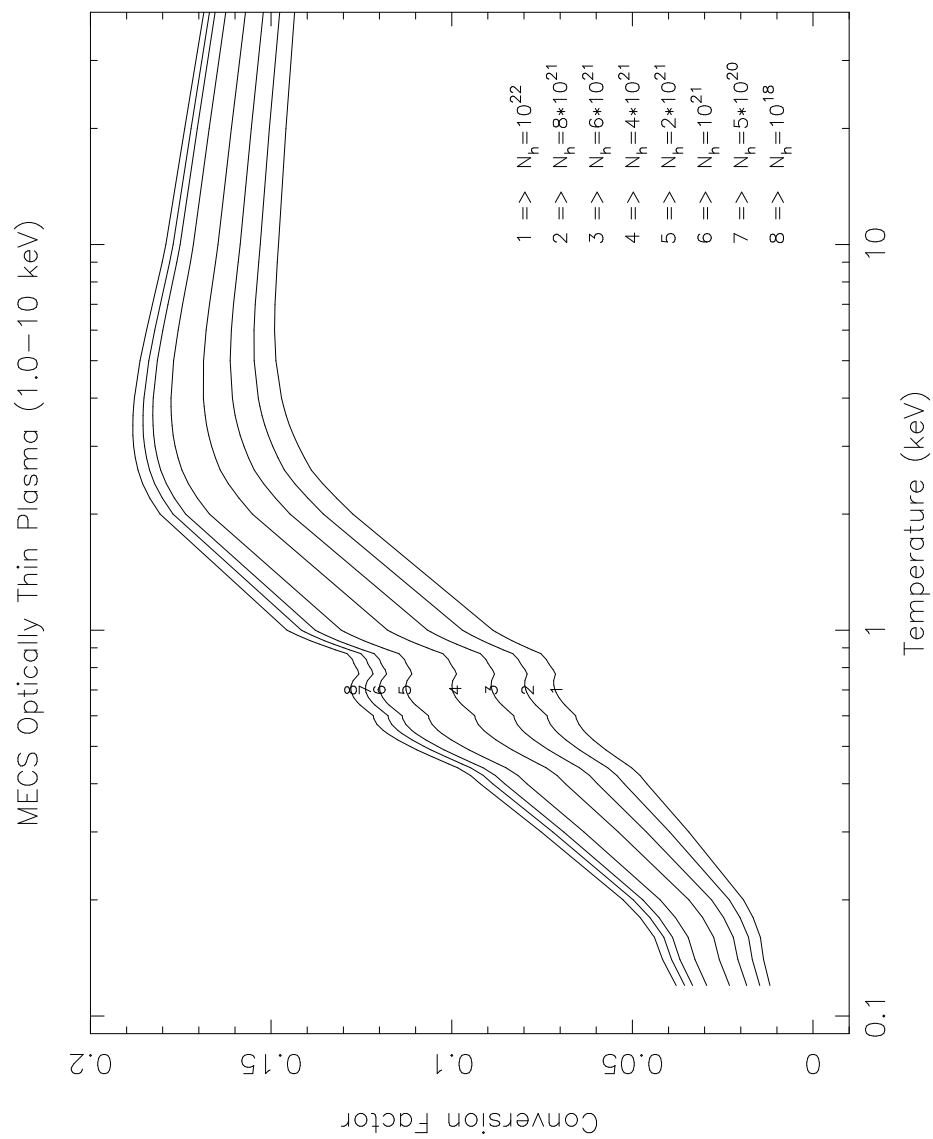


Fig.4.4.7

4.5. HPGSPC⁴

4.5.1. Introduction.

The High Pressure Gas Scintillation Proportional Counter (HPGSPC) is one of the narrow field instrument of the scientific payload of SAX. The HPGSPC is a 5 atm. (Xe plus 10% of Helium) Gas Scintillation Proportional Counter, sensitive in the 4-120 keV energy band with a nominal energy resolution of about 4% or better at 60 keV. The wide spectral band and the good energy resolution makes this detector capable of studying in detail the narrow cyclotron lines present, both in emission and absorption, above 20 keV in the X-ray spectrum of some X-ray celestial sources. It will also complement the iron line studies of the concentrators/spectrometers and the source continuum observations of the concentrators and the PDS, performing high resolution spectroscopy in the not yet well studied hard (4-120 keV) X-ray band.

4.5.1.1. The Detector.

A schematic of the detector is reported in Fig 1. The main characteristics are summarized in Table 1. The electron cloud produced by the absorption of a X-ray photon is drifted in a 10 cm "Drift Region" by a 160 V/cm/atm reduced electric field toward a high field (up to 2.5 kV/cm/atm) 1 cm "Scintillation Region". The 170 nm VUV light produced in the Scintillation Region is detected by an array of 7 Photomultipliers (Pmts) with 3.19 inches of diameter each, positioned about 7 cm below the Scintillation Region. The geometric useful area of the HPGSPC is 450 cm². To reduce the residual background the detector is shielded with 1 mm of lead + 2 mm of tin around the sides and on the bottom (the shield is not reported in Fig. 1).

Tab. 1 HPGSPC - Detector

Exposed geometrical area	450 cm ²
Body of the cell	Titanium 3 mm thick
Entrance window	Beryllium 1.3 mm thick
Depth of drift region	10 cm
Depth of scintillation region	1 cm
Depth of back region	6.4 cm
Suprasil UV exit window	7 * 3.3" diam. 6 mm thick
Suprasil UV read-out	7 * 3.19" diam. Pmts, EMI D319
Voltage applied to the drift region	8 kV
Voltage applied to the scintillation region	12 kV
Filling gas	Xe + 10% He
Filling pressure	5 atm
Outer diameter	42.5 cm
Useful diameter	24 cm

⁴ Contribution by G. Manzo, S. Giarrusso, A. Santangelo

4.5.1.2. Collimator

On the top of the detector a 10 cm collimator defines an almost circular Field of View (FOV) of $1.1^\circ \times 1.1^\circ$ FWHM. The collimator consists of almost circular tubes made with 10 μm of lead covered with 50 μm of aluminum and has a transmission of 75%. It can be rocked back and forth up to 3° degrees off the coaligned position. Five simmetrically rocking steps are foreseen respect to the on axis position: $\pm 20'$, $\pm 40'$, $\pm 60'$, $\pm 90'$, $\pm 180'$. The minimum exposure time in each step position is 48 sec with a transit time from two different position of less than 3 sec.

4.5.2. General Operation Principle.

4.5.2.1. Interaction of X-ray in Xenon.

Following the absorbtion of a X-ray photon via photoelectric effect the Xenon atom emits a primary photoelectron from an inner shell. The emitted primary photoelectron colliding with other Xenon atoms produces a cloud of secondary electrons at the position of the X-ray absorbtion. The number of secondary electrons produced is proportional to the energy of the primary photoelectron $E_x - E_b$ where E_x is the photon energy and E_b is the binding energy.

The vacancy in the inner shell is, then, filled and the corresponding energy may be released in two different ways: an X-ray fluorescence photon may be emitted or alternatively an Auger electron is emitted from the outer shell. In the case of Auger emission a cloud of secondary electrons is produced in the same position of the cloud generated by the primary photoelectron. The total number of secondary electrons in the cloud is proportional to the energy of the incident X-ray photon. In the case of fluorescence emission, a second cloud is produced at the point in wich the fluorescence photon is absorbed. The energy of the incident X-ray is then proportional to the total number of electrons of the two clouds.

The electron clouds, after drifting in the low field region, enter the Scintillation Region and produce a UV light burst proportional to the number of electrons in the cloud (i.e. to the X-ray photon energy) that is detected by the PMTs.

In the case of the HPGSPC the absorbtion of a X-ray photon occurs in the L (or lower order) shell if $E_x < 34.6$ keV (the Xenon K shell binding energy). In this case only a single cloud is produced, because the probability of atomic relaxation via Auger effect is much

higher than fluorescence (Auger probability is about 89%) and, in any case, the mean penetration depth of the L fluorescence photon in 5 atm Xenon is less than 1 mm. Only a single VUV light burst will then be produced and the HPGSPC electronics will detect what is defined a "single" event.

For incident X-ray with $E_x > 34.6$ keV the probability to interact with the K shell is 86%, while the probability that the atom relaxes via a K_α (29.7 keV) or K_β (33.8 keV) fluorescence photon is 87.5%. Because the main penetration depth of the K fluorescence photon is 4 cm (in 5 atm Xenon), a pair of separate, but correlated, electron clouds (or VUV light bursts) can be produced. In this case the HPGSPC electronics can detect both "single" and "double correlated" events.

4.5.2.2. Scientific modes.

The HPGSPC can be operated in three different "scientific" modes:

- "Single Event" mode
- "Fluorescent Gated" mode
- "All Events" mode

In "Single Event" (SE) mode only X-ray photons detected as a single VUV light burst are collected. The SE mode can be used in the full HPGSPC energy range and is the only mode for X-ray events with energy below 34.6 keV.

In "Fluorescent Gated" (FG) mode only incident X-ray photons producing "double correlated" events are accumulated. Two VUV light bursts are detected as "double correlated" if they differ in time less than 40 μ sec (that is the maximum transit time in the Drift Region) and at least one is due to a K_α or K_β fluorescence photon. The FG mode is used only above 34.6 keV. In the FG mode a great improvement in the Signal to Noise ratio is obtained: the detection of a "double correlated" event provide a unique signature for a true X-ray event and, in this sense, can be used to discriminate against a non X-ray background event.

In the "All Events" mode both "single" and "double correlated" events are accumulated. Defined in the entire energy band of the HPGSPC, the "All Events" mode maximizes the detection efficiency of the Instrument.

4.5.2.3. Collimator configuration modes.

The Collimator configuration modes for the HPGSPC are basically :

- Cyclic configuration mode
- Non cyclic configuration mode.

The cyclic mode allows the continuous monitoring of alternatively background (OFF SOURCE) and source + background (ON SOURCE) flux.

1) "Two Sided Cycle", in which the background flux is alternatively monitored at $+3^\circ$ and -3° (maximum rocking angle) of the on axis position. This is considered the default mode mode (COLLIMATOR LAW = 1, in the instrument form contained in the proposal)

2) "One Sided Cycle", in which the background flux is monitored on only one side at $+3^\circ$ or -3° rocking angle. (COLLIMATOR LAW = 2, in the instrument form contained in the proposal).

3) In the non cyclic mode the collimator is held fixed on axis. This mode may be used for very strong sources, when the background is negligible (COLLIMATOR LAW = 3, in the instrument form contained in the proposal)

The stay time at each position ranges from 8 sec to 2048 sec, with a step of 8 sec. The minimum stay time available to observers is 48 sec, which is compatible with the average lifetime of the collimator.

4.5.3. Characteristics and Performance.

4.5.3.1. Detection efficiency.

The Quantum Efficiency of the HPGSPC is limited at lower energies by the transmission of the beryllium entrance window whose schematic is reported in Fig. 1. The window consists of two layers of beryllium 0.5 and 0.8 mm. thick, brazed on top and bottom of a support frame in beryllium. This core self-supporting structure is welded to the titanium body via an aluminum/titanium transition ring.

At higher energies the efficiency is mainly limited by the absorption of X-rays in Xenon. The efficiency as a function of energy can be calculated as follows:

$$\varepsilon(E) = fW(E)(1 - \exp(-\mu(E)d))$$

where $W(E)$ is the window transmission, $\mu(E)$ is the photoelectric absorption coefficient, d is the depth of the drift region and f is the efficiency of the electronics to recognize a true X-ray.

In Fig. 4.5.2 is reported the HPGSPC Effective Area (in cm²) as a function of the energy. In the calculation have been taken into account the transparency of the collimator (75%) and, above 34.6 keV, the escape fraction of the fluorescence photons not absorbed within the gas volume.

4.5.3.2. Energy resolution and linearity.

The collimated on axis energy resolution of the HPGSPC is mainly limited by the statistics of electron production in the absorption region and VUV light production in the Scintillation Region.

For X-ray events uniformly distributed on the entrance area of the detector the energy resolution is strongly degraded and is almost independent of the energy. The degradation of the energy resolution is due to the dependence of the measured energy E_m (Sum Signal, i.e. sum of the signals of the seven Pmts) on the (x,y) position of the event. Indeed it's the total effective solid angle subtended by the Pmts that strongly depends on the (x,y) position of the event.

The intrinsically good energy resolution can in principle be restored by multiplying the Sum Signal (E_m) by the ratio K_c of the total effective solid angle "on axis" to the total effective solid angle subtended by the Pmts array at the (x,y) event position:

$$E_c = E_m * \frac{\Omega_T(0,0)}{\Omega_T(x,y)} = K_c * E_m$$

$$\Omega_T(X,Y) = \sum_0^6 \Omega_i(X,Y)$$

where $\Omega_i(x,y)$ is the effective solid angle subtended by Pmt i .

The energy correction procedure requires, then, to use an appropriate (x,y) position reconstruction algorithm to evaluate the K_c ratio from an experimental look-up table implemented onboard.

The HPGSPC Full Area energy resolution (i.e. after performing energy correction) is well approximated by:

$$\frac{\Delta E}{E} = 11 * \left(\frac{E}{6} \right)^{-0.5} \% FWHM$$

The energy response of Xenon filled GSPCs is assumed to be linear throughout the entire energy range of operation. Experimental results on the scientific model of the HPGSPC confirmed the linearity of energy response in the 4-120 keV band. Only recently, however, have been reported experimental measurements that show a very small discontinuity in linearity (about 180 eV) at the K absorption edge in Xenon (1 atm) at 34.6 keV. A discontinuity of about 140 eV has also been measured in the Xenon L absorption edge at 4.8 keV. However, its effect is negligible for the HPGSPC because, due to the window cut, the quantum efficiency at that energy is low.

4.5.3.3. Background.

Several components contribute to the background level of the SAX-HPGSPC. A major background source is the diffuse isotropic atmospheric and cosmic X and Gamma ray component that manifests itself as an aperture flux that depends upon the FOV of the collimator and as indirect background induced through shield penetration. A second component is due to primary cosmic rays (mostly protons) and geomagnetically trapped particles that interact directly with the detector or, interacting with the spacecraft and the atmosphere, give rise to gamma rays penetrating the detector through the shield. A third component is due to electrons and neutrons mainly produced as a result of the primary cosmic ray interaction with the atmosphere.

For the HPGSPC background reduction will be achieved in three ways:

- Passive shielding; 1 mm of lead + 2 mm of tin cover all direction other than the FOV of the instrument.
- Burst Length (BL) selection; only events that produce a VUV light burst whose duration is within the upper and lower thresholds (experimentally determined for X-rays) are recognized as true events.
- Radius selection; events detected outside the selected radius (maximum value 12 cm) are rejected as suspected background events coming from the detector wall.

Simulation results for the HPGSPC show that the background due to the diffuse X-ray component is small and the background count rate due to direct interaction of charged particle in the gas can be strongly reduced with BL selection. The dominant residual background component is that produced by high energy photons that are absorbed in the gas via photoelectric interaction after having suffered multiple scattering in the instrument body.

A value of 2×10^{-3} counts $\text{sec}^{-1} \text{keV}^{-1} \text{cm}^{-2}$ (of the detector area) has been estimated for the intrinsic residual background when the HPGSPC is operated in SE mode. In FG mode the intrinsic residual background may be reduced up to an order of magnitude.

4.5.3.4. Gain Monitoring.

Four fixed calibration sources of mixed Fe^{55} and Cd^{109} (filtered with chromium) will be used to monitor the detector gain and to calibrate the energy response for long term variation. Each source is mounted on a single hexagonal cell on the collimator following the scheme reported in Fig. 1. The 22 keV line of the Cd^{109} source in the central position is also used to automatically control the gain within 0.5% by acting on the high voltage supplies of photo multipliers.

4.5.3.5. Timing.

The maximum precision in the event tagging time is 15.258 μsec . The actual timing precision depends on transmission mode chosen (see section 4.5.6).

4.5.4. Observation feasibility

4.5.4.1. Minimum Detectable Count Rates

The HPGSPC sensitivity is essentially limited by the background flux. The minimum detectable source flux (in photons $\text{cm}^{-2} \text{sec}^{-1} \text{keV}^{-1}$) can, then, be estimated from:

$$F_{\min} = \frac{K_{\sigma}}{\varepsilon} \sqrt{\frac{B}{A \Delta E t}}$$

where K_{σ} is the number of standard deviations by which the counts attributable to a source exceed the background; B is the Background flux in counts $\text{cm}^{-2} \text{sec}^{-1} \text{keV}^{-1}$, A is the geometric area of the HPGSPC, ε is the efficiency and ΔE is the energy range and t is the observation time. In Fig. 4.5.3 the minimum detectable source count rate (counts sec^{-1}) is reported as a function of observation time for 4-120 keV energy band and for 34-120 keV band in FG mode. The curves correspond to a value of K_{σ} equal to 5.

4.5.4.2. Expected Count Rates.

The expected HPGSPC count rate strongly depends on the incident source spectrum. In Figg. 4.5.4a, 4.5.4b, 4.5.4c the HPGSPC Energy to counts Conversion Factor (ECF) is shown for three different energy range (4-34 keV, 34-120 keV and 4-120 keV) and assuming a power law model as incident spectrum. In order to obtain the HPGSPC count rate in a given energy range, the incident source flux (in unit of 10^{-11} erg cm⁻² sec⁻¹) has to be multiplied by the ECF relative to that energy range.

4.5.4.3. Sensitivity to line features.

The sensitivity of the HPGSPC to the 6.4 keV iron line is shown in Fig. 5 where the minimum detectable line strength as a function of the continuum flux is reported for an observation time of 10^5 sec. In Fig. 5 is also reported the minimum detectable strength for an emission cyclotron line centred at 51 keV with a width of 15 keV (FWHM) and for an observation time of 10^5 sec.

4.5.5. Data Collecting Modes supported for observers.

Data from HPGSPC Instrument can be formatted and transmitted according to two basic operative modes:

- direct mode
- indirect modes (divided in spectral modes and spectral+indirect modes)

When the HPGSPC is operated in direct mode, basic information are transmitted for each qualified detected event. In indirect mode Burst Length and Energy spectra are accumulated on board and then transmitted to ground. In indirect temporal mode, beside the Energy and BL spectra, time profile spectra are accumulated. In a time profile spectrum data are collected in a few large energy channel on short timescale.

For direct, indirect and indirect temporal mode different submodes, specific to the types and number of information transmitted, are foreseen.

The modes supported for observers are the direct modes HP_DSC1 and HP_DSC2, in which the information telemetred are:

HP_DSC1

HP_DSC2

Ec	12 bits	0 - 120 keV	Ec	12 bits	0 - 120 keV
BL	8 bits	0.5 - 6.6 μ s	TT	16 bits	15.3 - 1E6 μ s
TT	16 bits	15.3 - 1E6 μ s	Fcorr	1 bits	
Fcorr	1 bits		Fcal	3 bits	
Fcal	3 bits				

where Ec is the corrected energy, BL is the burst length, TT is the time tag of the event, Fcorr is the correlation flag and Fcal is the flag for calibration event.

In the proposal form, in the field Data Collection Mode (DCM) the user should specify either HP_DSC1 (the default mode) or HP_DSC2

Events are transmitted in packets (source direct packet) of fixed length (8912 bits). The number of events per packet will be 215 for HP_DSC1 and 269 for HP_DSC2. This comes out to be equivalent to 41.45 bits/event in HP_DSC1 and 33.13 bits/event in HP_DSC2. Some of the events in the source packet are calibration events coming from the four fixed calibration sources. Calibration source contribute with about 8 counts/sec (at launch time). Beside the source packet, ratemeters source packet are produced by HPGSPC when operated in direct mode. Each ratemeters packet is generated in 21 sec. which means a telemetry of 424.4 bits/sec. Below is shown the different contribution of the HPGSPC science telemetry for the supported modes.

<i>Component</i>	<i>Telemetry (kbits/sec)</i>	
	HP_DSC1	HP_DSC2
X-ray source (n counts/sec)	0.041*n	0.033*n
Ratemeters	0.424	0.424
Calibration Source (8 counts/sec)	0.041*8	0.033*8
Background (100 counts/sec)	0.041*100	0.041*100

For strong sources the indirect modes may be used in alternative to direct modes. Software for analyzing the data taken in indirect modes may however not be available for the first year operation.

The indirect spectral mode is Indirect 3, containing the following information:

<i>Indirect 3 Spectra</i>	<i>Energy Band (keV)</i>	<i>N of channel</i>	<i>Bits/ channel</i>
Single Event Energy Spectrum	3.125 - 36.84	539	16
Single Event Energy Spectrum	36.84 - 128	729	8
Residual Event Energy Spectrum	1.125 - 96	759	8
Fluorescent Event Energy Spectrum	24 - 40	128	16
Single Event BL Spectrum	3.125 - 36.84	256	16
Single Event BL Spectrum	36.84 - 128	256	16
Residual Event BL Spectrum	1.125 - 96	256	16
Fluorescent Event BL Spectrum	24 - 40	256	16

Spectra in Indirect 3 (select DCM=HP_ISC3 in the proposal form) are transmitted in 5 packets (source indirect packets) of fixed length (8912 bits). Below are reported the different values of integration time that can be selected with the correspondent telemetry rate:

<i>Spectrum accumulation time (sec)</i>	<i>Telemetry (kbits/sec)</i>
1	44.56
2	22.28
4	11.14
8	5.57
16	2.79
32	1.39

The selected Spectrum accumulation time is to be specified in the proposal form.

Finally, for highly variable sources indirect temporal modes may be used in parallel with the indirect spectral mode.

As an example, the Indirect Temporal 3 (DCM=HP_ISC3_TP44) and, for strong source, Indirect Temporal 6 (DCM=HP_ISC3_TP48) can be chosen. They consist of 4 energy channels with 4 bits/channel for Indirect Temporal 3 and 8 bits/channel for Indirect Temporal 6, packed in single packets (source indirect temporal packet) of fixed length (8912 bits). The time bin and the correspondent telemetry rates for both modes are reported below:

<i>TB Bin Accumulation Time (msec)</i>	<i>Telemetry (kbits/s)</i>	
	HP_ISC3_TP44	HP_ISC3_TP48
0.9765	17.8	35.6
1.95	8.9	17.8
3.9	4.5	8.9
7.8	2.2	4.5
15.6	1.1	2.2
31.2	0.56	1.1
62.5	0.28	0.56
125	/	0.28

The selected TP Bin accumulation time is to be specified in the proposal form.

Figure Captions

Fig. 4.5.1. A schematic of the HPGSPC.

Fig. 4.5.2. The HPGSPC effective area as a function of the energy.

Fig. 4.5.3. The HPGSPC minimum detectable source count rate (5σ) vs. observing time in the 4-120 keV and 34-120 keV (FG mode) energy range.

Fig. 4.5.4. (a) The HPGSPC 4-34 keV flux to count rate conversion factors as a function of the photon index for a power law and three different column densities. (b) The same as a) but for the 34-120 keV range. (c) The same as a) but for the 4-120 keV range. (d) The 4-34 keV flux to count rate conversion factors as a function of the temperature for a thermal bremsstrahlung law and three different column densities. (e) The same as d) but for the 34-120 keV range. (f) The same as d) but for the 4-120 keV range.

Fig. 4.5.5. HPGSPC minimum detectable line strength as a function of the continuum flux in 10^5 observing time. A 51 keV Cyclotron line with a width of 15 keV FWHM, and a narrow 6.4 keV iron line are shown.

Fig. 4.5.6. The required time to detect at 5σ a flux variation as a function of the fractional variability for three source strength. The 4-120 keV energy range has been used.

4.6. The Phoswich Detection System (PDS)⁵

4.6.1. Introduction

The PDS is one of the narrow field instruments aboard SAX. It operates in the hard X-ray range (15-300 keV) and allows to perform in this range high sensitivity spectroscopy and temporal studies of celestial X-ray sources.

The PDS essentially consists of a square array of four independent NaI(Tl)/CsI(Na) scintillation detectors. A system of anticoincidence (AC) shields surrounds the sides and the front of the detectors and of the two collimators, one for each couple of detectors. The collimators can be independently rocked back and forth to allow the simultaneous monitoring of the source and background. The gain of the detector and of the associated linear electronics are continuously monitored and automatically controlled. They can also be periodically recalibrated.

The AC lateral shields are also used as gamma-ray burst monitors. Finally a particle monitor provides information on high environmental particle fluxes and triggers the action to prevent the damage of the detectors photomultipliers. A view of the PDS main elements is shown in Fig.1. The main PDS parameters are summarized in Table1. They are briefly described in the following subsections.

4.6.1.1. Detectors

Each of the four detectors is made of two crystals of NaI(Tl) and CsI(Na) optically coupled and forming what is known as PHOSWICH (acronym of PHosphor sandWICH). The scintillation light produced in each phoswich (PHW) is viewed, through a light guide of quartz, by a photomultiplier tube (PHOTOMULTIPLIERS). The NaI(Tl) acts as X-ray detector, while the CsI(Na) scintillator acts as an active shield.

The events (due to photons or charged particles) detected in each phoswich can be divided in three classes: those that deposit energy only in the NaI crystal (NaI events or "good events"); those that deposit energy only in the CsI crystal (CsI events); those that deposit energy in both crystals (mixed events). The events of the first class are accepted, while the events of the other two classes, as a rule, are rejected.

The rejection is performed using the different decay constants of the scintillations produced in the NaI (about 0.25 μ sec) and CsI (0.6 μ sec and about 7 μ sec for CsI). The analysis electronics, via its Pulse Shape Analyzer (PSA), can discriminate events of the three classes described above. The phoswich configuration is well known to provide a detector with a high efficiency at hard X-ray energies and a very low background level.

4.6.1.2. Anticoincidence shields

In order to further reduce the PHW background level, an anticoincidence shield system is

⁵Contribution by F. Frontera, D. Dal Fiume, E. Costa

implemented. It includes a lateral shield, a top shield and the shield of each PHW unit from the others.

4.6.1.2.1. Lateral shield

The lateral shielding system is made of 4 optically uncoupled slabs of CsI(Na) scintillators 10 mm thick, 275 mm high and 402 mm wide. Each slab is made of two pieces optically coupled together. Each slab is viewed, through a quartz light pipe by two 3" PHOTOMULTIPLIERSs with independent high voltage supplies. A light pulser obtained using a Am241 source encapsulated in a small NaI(Tl) crystal is inserted in each slab to provide a reference line to control of the detector gain. The summed signals from all PHOTOMULTIPLIERSs viewing the lateral shield are sent to a programmable threshold. All the events with amplitude higher than the given threshold reject simultaneous events from the PHW units. The events above threshold also generate a coincidence (COI) flag (see Sect.2.1.2), when the anticoincided events are requested to be transmitted. The lateral shielding system rejects a relevant fraction of the unwanted X-ray photons and charged particles impinging on the sides of the instrument.

4.6.1.2.2. Top shield

The top shield is made of an organic scintillator (BC-434) 1 mm thick that covers the X-ray entrance aperture. It rejects the background events due to charged particles entering the aperture of the instrument, inclusive of high energy electrons generated by interactions of Cosmic Rays with the materials of the instrument or with the satellite.

The scintillator is viewed by four 2" photomultipliers, each with independent high voltage supplies. The summed signals from these PMTs are sent to a programmable analog threshold like in the case of lateral shields (see Sect.1.2.1). Also a COI flag is transmitted when the anticoincided events are requested to be transmitted.

4.6.1.2.3. PHW shield

When an event detected from one of the 4 PHW units is in coincidence with an event detected from at least one of the other PHW units above their A/C thresholds, the event is rejected. In this way events that interact with one of the NaI scintillators via Compton effect, leaving only a fraction of its energy in the given scintillator, while other energy is lost in one of the other PHW units, are rejected. If the these anticoincided events are requested to be transmitted a COI flag is generated (see Sect.1.2.1).

4.6.1.3. Collimators

Between the top shield and the phoswich detection units, two X-ray collimators, one for each pair of phoswich detectors, define an hexagonal field of view, which, along the direction normal to the hexagon sides, is on the average 1.3 degrees Full Width at Half Maximum (FWHM). Each collimator, 20 cm high, is made of hexagonal tubes of tantalum 50 μm thick, bonded together. The inner surface of the tubes, for the first 4 cm starting from the base of each tube, is covered by a layer of tin (100 μm) and copper (50 μm). Each of the two collimators can be rocked back and forth with respect to its neutral position

independently of the other. Five symmetrical rocking steps are provided on each side of the neutral position. The maximum rocking angle is ± 3.5 degrees ($210'$) and the intermediate steps are $\pm 30'$, $\pm 60'$, $\pm 90'$, $\pm 150'$.

The minimum dwell time in a collimator step is 50 s, with a transit time from one position to the other of less than 3 seconds. This collimator configuration allows to monitor the background level at different offset angles simultaneously with source flux. It also allows to localize X-ray sources deriving the angular response of the collimators for the given source.

4.6.1.4. In-flight calibration systems

4.6.1.4.1. Fixed Calibration Source

Two calibration systems are provided. One makes use of a fixed calibration source (FCS), whose radiation allows to perform an automatic gain control of each detection unit. The FCS is a small cylinder of plastic scintillator doped with Am241, which is placed close to the X-ray entrance windows of the four phoswich units, exactly in the center of the detection plane.

A fraction (about 5 photons/sec) of the 59.6 keV photons emitted by Am241 are detected by each phoswich. These photons are emitted in temporal coincidence with alpha particles of about 5 MeV. These particles lose their energy in the plastic scintillator, giving light pulses easily detected by a small PMT coupled with the scintillator. This signal is used by PDS electronics to tag the photons simultaneously detected by the PHWs. The tagging efficiency is about 96%. The tagged photons are used by the PDS Instrument Controller to detect gain variations and to perform a continuous and automatic gain correction by acting on the high voltage supplies of the phoswich PMTs. The spectra of the tagged Am241 photons are transmitted among the housekeeping information.

4.6.1.4.2. Movable Calibration System (MCS)

The MCS consists of a radioactive source distributed along a wire about 32 cm long. Upon command, the source performs a scan of the entire field of view of the instrument above the collimators and top shield, uniformly radiating all the PHWs. In this way the absolute gain of the instrument is performed. The MCS will periodically be used to recalibrate the instrument for long term gain variations.

4.6.1.5. Gamma-Ray Burst Monitor (GRBM)

The lateral shields of the PDS (see Sect.1.2.1) are also used as detectors of gamma-ray bursts of cosmic origin (GRB). The signals from each of the slabs in a programmable energy band, nominally 60--600 keV, are sent to both a Pulse Height Analyser and a GRBM logic unit, where the trigger condition is checked. A GRB event accumulation is triggered when at least two of the four lateral shields meet the trigger condition. In this way we expect to reduce the rate of false triggers caused by interactions of high energy particles in the shields. If a GRB condition is verified, the burst time profile in the entire energy band from each of the four detectors is stored, together with the occurrence absolute time. The integration time

for count accumulation will be 10 ms for 10 s preceding the trigger, 0.5 ms for 10 s immediately following the trigger and 10 ms from 10 s to 2 minutes after the trigger time. Along with burst profiles, energy spectra integrated over 128 s covering the burst occurrence time period are acquired.

The expected 5 sigma sensitivity of GRBM in the 60-600 keV energy band is about 10^{-6} erg/cm². The capability to determine the burst location ranges from a few tenths of degree to several degrees, depending on burst strength and direction.

Data analysis of the GRBM require very specific and detailed knowledge of the instrument. Scientists interested in these data should submit, instead of a standard proposal, a letter of intent to the TAC (address is the same as for standard proposal). For further details on the GRBM contact F. Frontera (E-mail in sect.7).

4.6.1.6. Particle Monitor (PM)

A particle detector, made of a plastic scintillator viewed by a PMT, is mounted close to the PDS instrument allocation room. It allows to switch off the high voltage supplies of all the PMTs, exclusive of the PM PMT, when the environment charged particle intensity level will exceed a selectable threshold and to switch them on again when this level is below another selectable threshold.

TABLE 1. Main characteristics of the PDS instrument

PARAMETER	VALUE
Energy response	15-300 keV
Field of view (FWHM)	1.3 degrees (hexagonal)
Detection plane	4 NaI(Tl)/CsI(Na) square PHW units
Detector window size per unit	141x141 mm ²
Detector windows	top shield window + PHW window
Composition of Top shield window	0.8 μ m Al, 200 μ m Kapton, 1000 μ m BC-434 Plastic
Composition of PHW window	1500 μ m Be, 890 μ m Silicon, 76 μ m Kapton, 100 μ m Teflon, 0.1 μ m Al
NaI(Tl) thickness	3 mm
CsI(Na) thickness	50 mm
Geometric area per detection unit	200 cm ²
Collimator transmission	80% (on the average)
Energy resolution (@ 60 keV)	15% (on the average)
Time resolution	≥ 16 μ sec
Maximum throughput	50 Kbps
Energy spectra	1024 channels (max)

4.6.2. Instrument configuration

The instrument can be operated during source observations in different configurations depending on background rejection criteria and collimator rocking sequence chosen.

4.6.2.1. Background rejection configuration modes

4.6.2.1.1. Pulse shape discrimination

As discussed in the previous section, the pulse shape analysis of the phoswich events is continuously performed by the PSA electronics. Fig.2 shows a typical pulse shape spectrum in the 15-300 keV range. This is characterized by two peaks, one (on the left) due to NaI(Tl) events and the other due to CsI(Na) events.

The selection of good events is performed through the choice of the lower and the upper PSA thresholds. The configuration of the PSA parameters is in charge of the OCC with the supervision of the Hardware Group (HG) responsible for the PDS.

An already skilled Guest Observer (GO) can configure these thresholds by himself and, if chooses a proper DIRECT transmission mode (see later), can perform a more strict selection of good events, within the PSA thresholds, during off-line data analysis. This further selection requires a particular care, as it also impacts on the detection efficiency.

2.1.2 Anticoincidence (AC) modes

The AC logic allows to reject one or more of the following types of events detected by the detection units:

COI.1) Events simultaneous with events above the AC threshold of the lateral shields;

COI.2) Events simultaneous with events above the AC threshold of the top shield;

COI.3) Events simultaneous with events detected by other phoswich units with energy above their AC threshold.

If one or more of these COI events are accepted, they will be transmitted with the proper flag in Direct Transmission Mode (See Transmission Modes).

The baseline configuration of the AC logic rejects all the event types from COI.1 to COI.3.

2.2 Collimator configuration modes

Two fundamental configuration modes of the collimators are provided:

- Cyclic modes (CM);

- Non-cyclic modes (NCM).

2.2.1 Collimator cyclic modes

The CM modes allow the simultaneous and continuous monitoring of background and source-plus-background flux. With the "two-sided cycles", each collimator executes a repeating cycle between ON-source and OFF-source positions on both sides of the neutral position. With the "one-sided cycles", each collimator executes a repeating cycle between ON-source and OFF-source on only one side. The supported CM modes are those described in Table 2.

TABLE 2. Collimator Cycling Modes

MODE	STEPS
1	COLL1 ON / COLL2 offset +3.5 deg COLL1 offset -3.5 deg / COLL2 ON COLL1 ON / COLL2 offset -3.5 deg COLL1 offset +3.5 deg / COLL2 ON
2	COLL1 ON / COLL2 offset +3.5 deg COLL1 offset +3.5 deg / COLL2 ON
3	COLL1 ON / COLL2 offset -3.5 deg COLL1 offset -3.5 deg / COLL2 ON
5	COLL1 ON / COLL2 offset +2.5 deg COLL1 offset -2.5 deg / COLL2 ON COLL1 ON / COLL2 offset -2.5 deg COLL1 offset +2.5 deg / COLL2 ON
6	COLL1 ON / COLL2 offset +2.5 deg COLL1 offset +2.5 deg / COLL2 ON
7	COLL1 ON / COLL2 offset -2.5 deg COLL1 offset -2.5 deg / COLL2 ON
8	COLL1 ON / COLL2 ON COLL1 offset +3.5 deg / COLL2 offset --3.5 deg COLL1 ON / COLL 2 ON COLL1 offset -3.5 deg / COLL2 offset +3.5 deg
9	COLL1 ON / COLL2 ON COLL1 offset +2.5 deg / COLL2 offset -2.5 deg COLL1 ON / COLL 2 ON COLL1 offset -2.5 deg / COLL2 offset +2.5 deg
10	COLL1 ON / COLL2 ON COLL1 offset +3.5 deg / COLL2 offset +3.5 deg
11	COLL1 ON / COLL 2 ON COLL1 offset -3.5 deg / COLL2 offset -3.5 deg
12	COLL1 ON / COLL2 ON

COLL1 offset +2.5 deg / COLL2 offset +2.5 deg

13

COLL1 ON / COLL 2 ON

COLL1 offset -2.5 deg / COLL2 offset -2.5 deg

The default CM is 1, if background contamination from other known sources in the collimator offset position is not expected. Indeed CM 1 guarantees to perform the background measurement in a sky field which is independent of the source sky field. The GO must indicate in the proposal the maximum contamination permitted (MCP), in mCrab units, in the offset fields. On the basis of this information the SAX Operation Control Center (OCC) will determine the best satellite attitude where perform the requested observation. If CM 1 will not satisfy the GO constraints, other laws (CM 2 or CM 3) will be used. The GO may also select another supported law with no contamination constraints. Along with the MCP parameter, the GO will also provide the collimator dwell time per step (CDT) (minimum time duration 50 s) for the selected cyclic law.

4.6.2.1.2. Collimator Non-Cyclic Modes

With the non-cyclic modes the collimators are held in a given position during the POP duration. Non-cycling modes supported for the GO program are given in Table 3.

TABLE 3. Collimator No-cycling Modes

MODE	CONFIGURATION (offset in degrees)
14	COLL1 ON / COLL 2 ON
15	COLL1 ON / COLL2 offset +3.5
16	COLL1 ON / COLL2 offset -3.5
17	COLL1 offset +3.5 / COLL2 ON
18	COLL1 offset -3.5 / COLL2 ON
19	COLL1 ON / COLL2 offset +2.5
20	COLL1 ON / COLL2 offset -2.5
21	COLL1 offset +2.5 / COLL2 ON
22	COLL1 offset -2.5 / COLL2 ON

4.6.3. Performance

4.6.3.1. Detector window transparency and detection efficiency

The detector X-ray entrance window is made of the sum of the PHW window and top shield viewing window. The composition of both windows is reported in Table 1. The overall X-ray transparency of the PHW detector window with energy is shown in Fig.3.

The X-ray absorption efficiency of the NaI(Tl) detectors is defined as $\epsilon(E) = 1 - \exp\{-\mu(E)t\}$,

where $\mu(E)$ is the total absorption coefficient of the crystal and t its thickness. The absorption efficiency times the transparency of the PHW X-ray entrance window is shown in Fig.4.

4.6.3.2. Energy resolution

The energy resolution is defined as $R(E) = \Delta E/E$ where ΔE is the fwhm of a line at energy E shown by the detector. The energy resolution of the NaI(Tl) detection units is 15% at 60 keV, with a dependence on energy that can be approximated by the function

$$R(E) = K(E/60)^{-\alpha} \quad (1)$$

where $K = 0.15$, $\alpha = 0.5$ and E is expressed in keV.

4.6.3.3. Background

The PDS background level is mainly due to the following components: diffuse cosmic X-ray background, prompt secondary gamma-rays due to interactions of primary cosmic rays (CR) and geomagnetically trapped protons (TP) with the detector materials and spacecraft, radioactivity induced in the detector materials by CR, TP and secondary neutrons, gamma-ray terrestrial albedo. In addition to these components, about 0.3 counts/s per PHW unit are due to FCS Am241 photons that are not tagged.

They contribute to the background spectrum at 60 keV and at about 30 keV. A background spectrum, measured during calibration tests, is shown in Fig.5. The peaks visible in the spectrum result from the combined contribution of FCS non-tagged events and X-ray fluorescence from collimator materials. The photon energy corresponding to a given channel in the plot of Fig.5 can be obtained from the set of data reported in Table 4.

TABLE 4 Preliminary energy to Channel conversion table

Energy (keV)	25	50	100	150	200	250	300
Channel No.	79	157	309	450	583	710	833

Modulation of the background along the orbit is expected because of the dependence of the cosmic rays flux and related terrestrial albedo on geomagnetic cut-off and of the passages of SAX through the South Atlantic Anomaly (SAA). Thanks to the very low inclination orbit, the modulation of the primary cosmic rays along the SAX orbit is very low. The flux of the geomagnetically trapped protons of energy ≥ 100 MeV experienced by SAX with time is shown in Fig.6. As a consequence of this modulation also the radioactivity and the neutral secondaries produced are modulated. In addition there is a build-up of the radioactivity that will influence the detector background level with time from the SAX launch, specially during the first few months.

The expected contribution of the different background components to the PDS background, about 3 months after the SAX launch are summarized in Table 5.

TABLE 5 PDS Background main components per PHW unit

Component	Counts/sec (15-200 keV)
X-ray cosmic background through FOV	0.2
Gamma-ray cosmic background through shields	0.78
Gamma-ray atmospheric background through shields	0.95
Induced radioactivity	3.5
Contamination from FCS	0.3
Total	5.73

The total count rate spectrum in three different energy channels is summarized in Table.6.

TABLE 6. PDS Background Counting rate spectrum per PHW unit

Energy range (keV)	Counts/sec	B (Counts/(cm ⁻² s keV))
15 - 40	1.6	3.2x10 ⁻⁴
40 - 80	1.3	1.63x10 ⁻⁴
80 - 200	2.8	1.15x10 ⁻⁴
200 - 300	2.8	1.4x10 ⁻⁴

4.6.3.4. Gain

By making use of the FCS sensor described in Sect.1.4, the relative gain of the PHW detectors is automatically controlled within 0.25%, while their absolute gain may be periodically monitored with an accuracy of 0.1%. The gain of the lateral shields is also monitored by using a line of equivalent energy of about 400 keV (the exact value depends on lateral shield slab) which is produced by the light pulser described in Sect.1.2.1. The accuracy of this calibration is within 1%.

4.6.3.5. Timing

The maximum precision in the event tagging time is 16 μ sec. The actual timing precision depends on transmission mode chosen. For that, see Sect.5.

4.6.4. Observation Feasibility with PDS

This section provides details of the performance of the PDS in order that potential users can quantify the feasibility of the proposed observations.

4.6.4.1. Minimum detectable source intensity

The minimum detectable source intensity I_s (photons/(cm² s keV)) with the PDS can be derived from the following general equation:

$$I_s = \frac{n\sqrt{2rB}}{\eta\sqrt{A_e}\sqrt{T}\sqrt{\Delta E}} \quad (2)$$

where n is the number of standard deviations (in the following we will assume $= 5$), A_e is the geometric area of the detector through the collimator that is exposed to the source, T is the observation time of the source and background, ΔE is the energy range, B is the background level (counts/(cm² s keV)) in the range ΔE , r is the ratio between the total area detector and A_e , and η is the PDS Spectral Conversion Factor SCF. The SCF is defined as the ratio between the count rate flux F_{ct} detected by the PDS in the energy channel ΔE and the photon flux F_{ph} incident on the detector in the same range. The SCF is obtained by convolving a given spectral model with the detector response function.

For PDS the SCF is shown in Fig.7 for two photon spectral indices of a power law; the intensity background B is given in Table 6 for four energy ranges, $r = 1.25$ and $A_e = 320$ cm² for an observation with collimator in Cycling Mode (see Table 2), that is, in the standard observation mode of the instrument.

Fig.8 shows the 5 sigma sensitivity of the instrument in three energy intervals (15-30, 30-80, 80-200 keV) as a function of the observation time for a Crab-like source. If the entire instrument is pointed at the source, like in the case of no-cycling mode NCM 14 (see Table 3), the minimum detectable intensity must be divided by $\sqrt{2}$.

4.6.4.2. Minimum detectable count rates

The minimum detectable count rates (counts/s) can be obtained from the expression of I_s (see equation above) by multiplying by η and A_e . The minimum detectable count rates in the range 20-200 keV are shown in Fig.9 as a function of the integration time for observations with two detectors pointing at the source and two measuring the background.

4.6.4.3. Expected count rates

The expected PDS count rates depend on the assumed incident photon spectrum. In order to facilitate count rate calculations, the following spectral model have been considered:

1. Power law with photon index α ;
2. Exponential law ($1/E \exp(-E/kT)$) with free parameter kT ;
3. Thermal bremsstrahlung with different temperatures (kT);
4. Black body with different temperatures (kT).

Fig.10 shows the Energy to Counts conversion Factor (ECF) for the above assumed models

and for the energy range 20-200 keV. For a given spectrum, the on-axis count rate expected in 2 detection units ($A_e = 320 \text{ cm}^2$) and in the 20-200 keV can be evaluated by multiplying the incident source flux (in units of $10^{-11} \text{ erg}/(\text{cm}^2 \text{ s})$) by the ECF value corresponding to the assumed spectrum.

4.6.4.4. Time variation sensitivity

The time $T(\text{s})$ needed to detect a fractional variation $b = (I' - I)/I$ in the flux intensity of a celestial source at a significance level of n sigma is given by

$$T = \frac{n^2}{A_e \eta I \Delta E} \left[\frac{2}{\beta^2} \left(1 + \frac{rB}{\eta I} \right) + \frac{1}{\beta} \right] \quad (3)$$

where I is the mean source intensity ($\text{ph}/\text{cm}^2 \text{ s keV}$) in the energy band ($E, E + \Delta E$) in keV and the other quantities were defined above (see sect. 4.1).

Fig.11 and 12 show the time needed to detect a 5 sigma fractional variation in the X-ray flux of a strong source (Cygnus X-1 in normal state) and a weak source (NGC 4151), respectively, for three energy bands (15-30, 30-80, 80-200 keV).

4.5 Sensitivity to emission lines

The general expression of the PDS sensitivity to emission lines in the spectrum of a celestial X-ray source is given by

$$I_l = \frac{1.31}{\eta \sqrt{A_e} \sqrt{T}} \sqrt{(rB + I_{cs}) \Delta E} \quad (4)$$

where I_l is the minimum detectable line intensity ($\text{ph}/\text{cm}^2 \text{ s keV}$) at energy E , B and I_{cs} are the average background and continuum source intensity, respectively, in the energy interval ($E - \Delta E/2, E + \Delta E/2$), where ΔE is the FWHM of the line of energy E as detected by the instrument for its finite energy resolution (see Sect.3.3). Fig.13 shows the 5 sigma sensitivity of the PDS to detect an emission line in the spectrum of a Crab-like X-ray source as a function of the line energy, for two source intensities (1 mCrab and 50 mCrab).

4.6.5. Data Collecting modes

The qualified events from the phoswich detectors are formatted and transmitted according to two basic operative modes:

- direct;
- indirect.

The typical transmission mode is the direct mode (DM). For strong or highly variable sources, indirect modes can be used.

4.6.5.1. Direct Modes

The supported direct modes with their associated information transmitted are given in Table 7.

TABLE 7. Supported PDS Direct Modes

Mode	ID ⁽¹⁾	COI ⁽²⁾	RT ⁽³⁾	E ⁽⁴⁾	T ⁽⁵⁾	Time resolution (ms)	Bytes
PD_DIR1	2	3	9	10	16	0.015	5
PD_DIR3	2	0	9	9	12	0.244	4
PD_DIR6	2	0	7	8	7	8	3
PD_DIR7	2	0	0	10	4	62	2
PD_DIR8	2	0	0	10	12	0.244	3
PD_DIR9	2	0	0	8	6	15.6	2
PD_DIR10	2	0	0	8	14	0.061	3
PD_DIR11	2	0	0	6	16	0.015	3

(1) Identification bits

(2) Coincidence flags bits

(3) Rise time bits (PSA channel)

(4) Energy bits (PHA channel)

(5) Time bits

Mode PD_DIR6 that is tuned for sources with low flux intensity (<50 mCrab). In the case of sources with mean flux intensity (50-500 mCrab) the recommended mode is PD_DIR3, while for strong sources, when high time resolution is required, the recommended modes are PD_DIR8 or PD_DIR10.

The telemetry allocation for observations carried out by means of direct modes can be deduced from Table 8.

TABLE 8. PDS Telemetry for Direct Modes

<i>Component</i>	<i>Telemetry (kbits/s)</i>
X-ray source (n cts/s)	$d*0.008*n$
Housekeepings	1.17
GRBM	0.287
Background (34.1 cts/s)	$d*0.008*34.1$

d is the number of bytes indicated in table 7 (last column)

4.6.5.2. Indirect modes

For strong sources, in alternative to the direct modes, Indirect modes are available.

4.6.5.2.1. Spectral Modes

TABLE 9. Supported PDS Indirect Spectral Mode

Mode name	bits/channel	No.of channels	Accumulation time(s)	Bit rate (kbits/s)
PD_IND_E88	8	128	1,2,4	3.9, 1.9, 0.96
PD_IND_E48	8	256	4,8	1.9, 0.96
PD_IND_E416	16	128	4,8	1.9, 0.96
PD_IND_E216	16	256	8,16	1.9, 0.96

The recommended mode is PD_IND_E88 with 4 s of integration time, that requires a 1 kbit/s telemetry. In alternative, GO can select one of the other supported modes, specifying, for each mode, spectrum accumulation time requested.

4.6.5.2.2. Temporal modes

In parallel with the above Indirect Spectral Modes, transmission of the count rate time profiles in few energy bands with high time resolution, down to 1 ms, is possible. The transmission modes of these data can be selected adding to the mode name of the indirect spectral mode selected, a code that indicates the temporal mode (e.g. _TP44) and a code that indicates if data are transmitted separated by units (_4), summed on pairs (_2) or summed on all units (_1). The bit rates reported are calculated for profiles summed on all units (_4).

TABLE 10. Supported PDS Indirect Temporal Modes

Code for temporal mode	bits/channel	No.of channels	Integration time (ms)	bit rate (kbits/s)
_TP18	8	1	1, 2, 4	7.7, 3.9, 1.9
_TP28	8	2	4, 8	3.9, 1.9
_TP48	8	4	8, 16	3.9, 1.9
_TP14	4	1	1, 2	3.9, 1.9
_TP24	4	2	2, 4	3.9, 1.9
_TP44	4	4	4, 8	3.9, 1.9

Therefore, to select:

- 1) the indirect spectral mode 128 channels 8 bits per channel
- 2) the indirect temporal mode 4 channels 4 bits per channel
- 3) the time profiles summed on all 4 units

the user indicates PD_IND_E88_TP44_4. This is also the recommended mode, with

integration time of 4 ms for time profiles and 4 s for spectra. In alternative GO can select one of the other combinations of indirect spectral and temporal supported modes, specifying the integration times.

FIGURE CAPTIONS

Fig.1. Schematic view of the PDS with its main elements.

Fig.2. Typical pulse shape spectrum of events detected by PDS detection unit 1 in the 15-300 keV energy range.

Fig.3. X-ray transparency of the NaI(Tl) X-ray entrance window.

Fig.4. X-ray absorption efficiency of the NaI(Tl) detection units times the X-ray entrance window transparency.

Fig.5. Background spectrum of PHW detection unit 1, taken during the calibration tests of the instrument.

Fig.6. Flux modulation of geomagnetically trapped protons of energy >100 MeV experienced by SAX with time.

Fig.7. Spectral Conversion Factor of the PDS as a function of photon energy for two photon spectral indices of a power law model.

Fig.8. Five sigma sensitivity of the instrument (two units pointing at the source) in three energy bands as a function of the observation time for a Crab-like source.

Fig.9. Minimum detectable count rate in the range 20 - 200 keV as a function of the integration time for two detectors pointing at the source and two measuring the background.

Fig.10. Energy to Counts Conversion Factor (ECF) for different models and for the energy range 20 - 200 keV. See text for its use.

Fig.11. Time to detect a 5 sigma fractional variation in the X-ray flux of Cygnus X-1 in normal state in three different energy bands.

Fig.12. Time to detect a 5 sigma fractional variation in the X-ray flux of NGC 4151 in three different energy bands.

Fig.13. Five sigma sensitivity of the PDS to detect an emission line in the spectrum of a Crab-like X-ray source as a function of line energy, for two source intensities (1 mCrab and 50 mCrab)

4.7. WFCs⁶

4.7.1 Introduction

There are two WFCs on SAX, built by the Space Research Organisation Netherlands at Utrecht. The WFCs are based on the coded mask principle, the reconstruction of the image takes place on ground. The field of view is 20 degrees square full width at half maximum (FWHM), the angular resolution 5 arcminutes (FWHM) and the energy band ranges from 1.8 to 30 keV with a resolution of 18% at 6 keV. The sensitivity is a few milli Crab in 10^4 s, depending on the source fluxes in the field of view.

The two identical WFCs point 180 degrees away from each other, both perpendicular to the sun vector and to the narrow field instruments. They will be able to perform spatially-resolved simultaneous monitoring of compact X-ray sources in crowded fields with high sensitivity, this enables systematic spectral variability studies of different types of compact X-ray sources over a large range of timescales. Surveys of pre-selected sky regions will be carried out to search for and study the characteristics of X-ray transients. The WFCs will perform imaging of X-ray emission (beyond the Fe-K complex between 6 and 8 keV) of extended hot plasma regions like the galactic supernova remnants and bright clusters of galaxies. In addition, the WFCs will be used to monitor large regions of the sky to signal the occurrence of previously unknown X-ray transients for follow-up studies with the narrow field instruments, such as black hole candidates and neutron stars in hard X-ray transients.

4.7.2 Instrument principle

The principle of the WFC is the Dicke camera [1]. A two-dimensional position and energy sensitive detector (multi-wire proportional counter) is placed behind an opaque metal screen with a pseudo random array of holes, a so called coded mask. X-ray sources in the field of view cast shadows of the mask on the detector, displaced according to the position of each source. A crosscorrelation afterwards reconstructs the position and flux of all sources in the observed part of the sky.

The WFC is used to obtain a high sensitivity over a large field of view and at the same time good angular resolution over the whole field (small mask holes). A schematic drawing of the SAX WFC is given in Fig. 4.7.1. Detector and mask have nearly the same size of 25.6×25.6 cm². A stainless steel structure between detector and mask allows the X-ray photons to reach the detector only through the mask and fixes the position of the mask 0.7 m away from the detector, this determines the Field Of View of 20 x 20 degrees Full Width Half Maximum. In front of the mask a 6 μ m thick kapton foil is placed as a thermal shield.

⁶Contribution by R. Jager

Table 1 summarizes the main characteristics of the instrument.

Wide Field Camera instrument characteristics	
Parameter	Value
Instrument:	
Field Of View (FWHM)	20 x 20 degrees
Angular resolution	5 arcmin
Source location accuracy	1 arcmin
Energy range	1.8 - 30 keV (31 channels)
Energy resolution	18% at 6 keV
Time resolution	0.5 ms
Maximum countrate	2000 c/s (Crab: 270 c/s)
Detector:	
Effective area @ 6 keV	520 cm ²
Gasmixture	2.1 bar, 90% Xe, 5% CO ₂ , 5% He
Detector pixels	768 x 768 (0.375 x 0.375 mm ²)
Detectorwindow	150 μ m Be
Window supportstructure	80% transparant
Mask:	
Mask size	256 x 256 mm ²
Mask element size	1 x 1 mm ²
Mask open element fraction	33% (effective 26.4%)
Mask composition	0.1 mm Fe, 4 μ m Au

The instrument can be used in two scientific modes: normal (imaging) mode and high time resolution mode. The time resolution in normal mode is 0.5 ms with a maximum eventrate of 2000 cts/s, in high time resolution mode the time resolution is 0.25 ms and the maximum eventrate is 6000 cts/s.

The sensitivity depends in principal on the pointing direction in the sky. Since each point source contributes to the Poisson noise in at least a quarter of the observed sky, the sensitivity decreases with an increasing number of observed point sources, i.e. when pointing towards the galactic plane. The best background-limited sensitivity is at the order of a few mCrab in 10⁴ s.

The maskpattern is square, it utilizes a socalled triadic residue URA pattern (Uniform Redundant Array), with 256 x 256 elements of 1 mm² each. Because of the near pseudo-random character of the pattern the *cyclic* autocorrelation of the mask pattern is three valued. The open fraction of the pattern is 33%.

The mask pattern is etched into a 0.1 mm thick stainless steel sheet, covered with gold for additional absorption. The open square holes are somewhat smaller than the basic 1 mm² elements, to allow for a grid pattern to maintain the mechanical integrity of the mask. This

reduces the overall mask transparency to 26.4%. Arguments for the choice of the instrument and mask configuration can be found in /3/ and /5/.

4.7.3 Image reconstruction, flux and position determination of celestial X-ray sources

The WFC data consists in principal of a list of events labeled with detector position, energy channel and time of detection. From this raw data one needs to determine for all detected celestial X-ray sources fluxes and positions (in case of extended sources also morphology). This will all be done on ground. The first task comprises of a reconstruction of the observed sky in an optimal time and energy channel interval in order to obtain information on detections of X-ray sources. A number of reconstruction methods have been described in the literature (e.g. /3/). We briefly describe here the method of cross correlation between detector image and mask pattern; a full description can be found in /3/.

Representing the detector image by a two-dimensional matrix **D**, the mask pattern by **M** and the true sky image by **S**, the exposure of **S** through **M** is given by the convolution (X)

$$\mathbf{D} = \mathbf{S} \times \mathbf{M} \quad (1)$$

Cross correlation (*) of **D** with a to-be-defined reconstruction matrix **R** reveals an estimate **S'** of **S**,

$$\mathbf{S}' = \mathbf{D} * \mathbf{R} = \mathbf{S} \times (\mathbf{M} * \mathbf{R}) \quad (2)$$

The reconstruction is perfect if **R** satisfies the condition

$$\mathbf{M} * \mathbf{R} = \mathbf{I} \quad (3)$$

where **I** is the identity matrix. If **M** is based on a pseudo-random pattern, **R** can be found and is uniquely given by **M**, the pattern of **R** is equal to the pattern of **M**.

If **D** contains complete uncorrupted shadows of **M**, equation (3) is always exactly matched. However, in a detector-mask configuration such as employed in the SAX-WFCs (i.e. with equally sized mask and detector) **D** only contains a complete ≠shadow of **M** for the on-axis position, and even in this case the detector window support structure blocks about 20% of the shadowpattern. This implies that nondiagonal terms of **M** * **R** will be zero only on average, so-called 'coding noise' emerges. The reconstruction of a single sky pixel **k** can then be represented by

$$s'_k = s_k + \sum_{i \neq k} s_i \cdot f_{i,k} \quad (4)$$

where s'_k is the reconstructed intensity at sky pixel k , s_k the true intensity, $f_{i,k}$ a factor representing the cross talk between different sky pixels introduced by the coding noise. equation (4) illustrates that coding noise is in fact deterministic: if the configuration of sky sources is known, the cross-talk term may be evaluated and its influence on the estimate of s_k eliminated. In practice, suppression of coding noise may be accomplished by an iterative method. Such a method is 'iterative removal of sources' (IROS, see e.g. /2/ and /3/). In IROS, each step involves the subtraction of simulated point source exposures in the detector plane, where the point sources are those which are significant with respect to the noise in the cross correlation of that detector image. A cross correlation on the result detector image contains less coding noise and provides the means to evaluate weaker sources for a subsequent iteration. The final product of IROS is a sky image with almost no coding noise and no sources. The subtracted sources are then recovered in this image.

IROS is one of three procedures to optimize the signal-to-noise ratio of the reconstruction as determined by the cross correlation given by equation (2). The other two involve the following:

1. The Poisson noise may be suppressed by differently weighing subsections of the detector plane during cross correlation. The idea behind this technique may be thought of as follows: consider the case when one strong and one weak point source are in the observed sky whose exposures have a small overlap in the detector plane. We may omit counts in this overlap during the reconstruction of the weak source, thus eliminating the strong contribution in Poisson noise from the strong source. This may improve the signal-to-noise of the weak source several tens of percents. Generally, this improvement may be achieved by weighing detector subsection in stead of omission.
2. The value of $\mathbf{R}$ (uniquely given by $\mathbf{M}$, see /3/) does not account for possible disturbing influences on the imaging from the detector window support structure. Part of this disturbance may be eliminated by redefining $\mathbf{R}$. The rest may be eliminated by subtracting in the detector plane, before the cross correlation, an estimate of the contribution by sky and non-sky background. The total countrate of the background is expected to be about 130 c/s in the full energy passband (cf. the expected countrate for the Crab X-ray source of 270 c/s).

The results of the complete reconstruction are two images, one representing estimates of the intensity per sky pixel and the other estimates of the Poisson noise standard deviation per pixel.

In order to determine flux and positions of each source in the reconstructed sky it is necessary to fit the observed data with the correct Point Spread Function (PSF), otherwise large errors in the determination of the flux will occur.

The PSF is a function of the photonenergy, the angle of incidence, the noise of the position-readout system, the spatial response to the reconstruction algorithm and the pointing stability.

4.7.4 Spectra and light curve production

With the procedure briefly discussed in the previous paragraph, knowledge of positions and fluxes of the X-ray sources is at hand. Subsequently this information can be used to perform a more detailed analysis, i.e. determination of spectrum and lightcurve (or upper limits on the intensity).

The spectrum of each source can in principle be determined in 31 energy channels, from 1.8 to 30 keV.

For timing analysis purposes, the highest time resolution can be achieved in principle on a photon by photon basis, the resolution is then 0.5 ms in Normal Mode. One method is to perform a so-called direct correlation of each photon with the appropriate part of the maskpattern corresponding to the source to be analysed. Another possibility is to apply a Maximum Likelihood Fitting Method.

The method will be described elsewhere

4.7.5 Performance aspects

4.7.5.1 Effective area, background, sensitivity and countrate estimations

The detector effective area of the WFC's is limited by the gas density in the detector at high photon energies, at low energies the transmission of the detector window is the limiting factor. The area is furthermore partially blocked by the detector window support structure. For off-axis sources both the mask-detector structure and the detector window support structure act as collimators with a two-dimensional triangular response.

The overall instrument effective area of the WFC is further reduced by the mask open fraction. The sensitivity of a coded mask camera however is only partly a function of the effective area. Because of the fact that all sources are detected against the diffuse X-ray background and all other sources in the FOV, the sensitivity is strongly dependent on these factors. Fig. 4.7.2 shows examples of the sensitivity for sources at high galactic latitudes and at the galactic centre region. Also the sensitivity for changes in the flux is given for these sample skyregions (Fig. 4.7.3)

The mask open element fraction that was chosen for the SAX-WFCs, i.e. 33%, has been optimised to achieve maximum signal to noise ratios for typical observations. See /5/ for a detailed analysis.

Fig. 4.7.4 shows the count rate to flux conversion factor for both a power law and a thermal model, for two different column densities. Fig. 4.7.5 shows some simulation results for the sensitivity of the WFC for spectral parameters. These simulations were performed under the assumption that the source is detected against the diffuse X-ray background and that there is a total of 500 mCrab in the field of view.

The background of the WFC consists of the following contributions:

- detector background, estimated to be 20 c/s
- diffuse X-ray background, extrapolated from the COMIS experiment in MIR/KVANT, 110 c/s
- other sources in the field of view, strongly pointing dependent.

4.7.5.2 Position resolution

The position resolution on the detector is, among others, a function of energy of the incident photon and of the incident angle.

In sky coordinates the angular resolution is determined by the maskelement size and the distance of mask to detector. In the case of SAX it is 5 arcmin. The position accuracy however is limited only by the pointing reconstruction accuracy of the satellite and by the statistics of the observation. In SAX it will be better than 1 arcmin.

4.7.5.3 Energy resolution

The energy resolution is typical of a proportional counter, it can be written as a Gaussian distribution with a standard deviation σ where $\sigma(E)$ is given by:

$$\sigma(E)=0.18 \cdot E^{-0.5}$$

The exact relation will be derived from calibration activities.

4.7.5.4 Instrument modes and timing capabilities

In normal mode (WFC_NOR) each event is labelled with 26 bits, 21 bits for the position and 5 energy bits. After every four events 8 bits time are added. The average number of bit per event is therefore 28. The time resolution is 0.5 ms. The time of each of the four events can be estimated by simple or by randomized interpolation.

In high time resolution mode (WFC_HTR), the time resolution is 0.25 ms, the maximum event rate can be as high as 6000 cts/s and no event position information is produced, this mode is useful for timing analysis of strong sources.

For diagnostic purposes two diagnostic modes are available, no onboard processing takes place and per event all raw data are available. For particle background evaluation purposes a background analysis mode is implemented.

4.7.6 Literature

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Figure Captions

Fig. 4.7.1. Schematic picture of the WFC.

Fig. 4.7.2. The minimum detectable flux (5σ) as a function of the observing time for a source at high galactic latitude and a source in the Galactic centre region (i.e. a crowded region).

Fig. 4.7.3 The time necessary to detect flux change at 5σ vs. the fractional source change for a 1 mCrab source at high latitude and a 1 Crab source in the galactic centre.

Fig. 4.7.4 The count rate to flux conversion factor for a power law and a thermal model. Two column densities (10^{21} and 10^{22} cm^{-2}) have been explored.

Fig. 4.7.5 Percentage error for spectral parameters. (a) Power law: error on the spectral index. (b) Power law: error on the column density. (c) Thermal model: error on the temperature. (d) Thermal model: error on the column density.

4.8. NFI Overall Scientific Performances⁷

Spectral capabilities of single NFI instruments

The spectral capability of each instrument is best summarized and illustrated by evaluating the percentage error on the parameters of fitting models. We adopt here the simplest and most general model, i.e. an absorbed power law. In Fig. 4.8.1 the percentage error (68%, 2 interesting parameters) for both the photon spectral index Γ of the power law and the column density NH of the (cold) absorber are shown for the LECS, as a function of the unabsorbed 2-10 keV flux, for three values of Γ (1.5, 2, 2.5) and two values of the column density (10^{20} and 10^{21} cm⁻²). Two different observing times, 10^4 s and 10^5 s have been explored. The adopted extraction region has a radius of 6'.3, corresponding to 80% encircled power at 0.28 keV. As the point spread function becomes narrower at higher energies, this assumption is rather conservative. Fig. 4.8.2 shows the same quantities for the MECS (but for $NH=10^{21}$ and 10^{22} cm⁻²). In this case, the radius of the extraction region is 2'.5, corresponding to 80% encircled power practically over the whole MECS energy range. Finally, Fig. 4.8.3 shows the photon index percentage error for the HPGSPC and the PDS. The figure is obtained assuming that the instruments point the source half of the time, the remaining half being devoted to the background estimate.

Overall spectral capabilities of the NFI instruments

As the most valuable feature of SAX is the wide band, it is likely that almost all observations with the NFI will make use of more than one instrument. Two typical configurations can be foreseen: a first one which makes use of the two imaging instruments, LECS and MECS, and a second one making use of all four instruments.

The sensitivity for the first configuration (LECS+MECS) is best illustrated by means of a Mewe et al. model, as probably such configuration will be mainly adopted to study hot thin plasmas. In Figs. 4.8.4 (a-d) the percentage error (68% confidence level, 1 interesting parameter) for the temperature, the iron abundance and the abundance of the other metals are shown, as a function of the unabsorbed 0.5-4.5 keV incident flux, for four values of the temperature (1, 2, 4 and 8 keV) and a solar chemical composition. Two different observing times (10^4 and 10^5 s) have been explored. The assumed column density is 2×10^{20} cm⁻².

The above sensitivities have been obtained assuming a point source. Typical hot plasma sources (e.g. Clusters of Galaxies) can appear extended. We have therefore calculated the percentage errors also for a 5' extended source. The results for the four above temperatures and a metal abundance equal to 0.5 (more appropriate for a Cluster of Galaxies than the solar value) are shown in Figs. 4.8.5 (a-d).

The second configuration (all instruments) is best illustrated with power law spectra. In Figs.

⁷Contribution by G. Matt

4.8.6 (a-c) the percentage error (68% confidence level, 2 interesting parameters) for the photon spectral index, as a function of the unabsorbed 2-10 keV incident flux, is shown for three values of Γ (1.5, 2, 2.5) and three values of the column density (10^{20} , 10^{21} and 10^{22} cm⁻²). Again, both $T_{\text{obs}}=10^4$ s and $T_{\text{obs}}=10^5$ s have been explored. In Figs. 4.8.7 (a-c) the percentage error for the column density is shown.

Figure Captions

Fig. 4.8.1. The percentage error on the LECS determination of the spectral index Γ and the column density for an incident absorbed power law as a function of the unabsorbed 2-10 keV flux. Three photon spectral indices (1.5, 2, 2.5), two column densities (10^{20} and 10^{21} cm $^{-2}$) and two observing times (10^4 and 10^5 s) have been studied.

Fig. 4.8.2. The same as for Fig. 4.8.1 but for the MECS; note that the chosen column densities are partly different (10^{21} and 10^{22} cm $^{-2}$).

Fig. 4.8.3. The percentage error on Γ vs. 2-10 keV incident flux for the HPGSPC and PDS.

Fig. 4.8.4. The percentage error on the temperature T , the iron abundance A_{Fe} and the abundance of elements other than hydrogen and iron, A_Z as a function of the 0.5-4.5 keV unabsorbed flux from a point source. A LECS+MECS configuration has been adopted. A Mewe et al. plasma model has been used. $NH=2 \times 10^{20}$ cm $^{-2}$ and $A_{Fe}=1$, $A_Z=1$ have been assumed. Two different observing times (10^4 and 10^5 s) and four temperatures (1 keV, panel a; 2 keV, panel b; 4 keV, panel c; 8 keV, panel d) are shown.

Fig. 4.8.5. The same as for Fig. 4.8.4, but for a 5' extended source with $A_{Fe}=A_Z=0.5$.

Fig. 4.8.6. The percentage error on Γ as a function of the 2-10 keV unabsorbed flux of an incident power law. The 4 NFI instruments configuration has been used. Three photon spectral indices (1.5, 2, 2.5) and two observing times (10^4 and 10^5 s) have been studied. Panel a) refer to $NH=10^{20}$ cm $^{-2}$, panel b) to $NH=10^{21}$ cm $^{-2}$ and panel c) to $NH=10^{22}$ cm $^{-2}$.

Fig. 4.8.7. The same as for Fig. 4.8.6 but for the column density.

4.9. Overall Telemetry budget and allocation to instruments⁸

4.9.1. Introduction

To accommodate the wide range of measurements that is intended to perform with SAX a very flexible system for programming the telemetry allocation between the instruments, under ground control, has been incorporated onboard. This system is based on the coordinated programming of the telemetry modes of the instruments, taking into consideration the tape recorder speeds available, maximum data volume transmittable to the ground in a single orbit, basic telemetry requirements for each instrument, and eclipse by Earth of the source under observation as constraints. However, to the purpose of proposing a certain observation with SAX the user needs only to consider the telemetry rate his observation requires.

Telemetry allocation for each instrument will be programmed by the SDC/OCC team on the basis of the count rate and DCM specified by the observer in the proposal form.

All the instruments possess direct telemetry modes with various options allowing data on single events to be collected. Thus when an observation requires the use of these modes in all (which is the default) or part of the instruments, the possibility exists that an instrument may be under using its telemetry allocation, and in extreme cases that an instrument may require more telemetry than its allocation. Consequently, an algorithm has been incorporated on board to allow momentary reallocation of unused telemetry on the timescale of about one second. Note that this reallocation does not apply to the instruments operating in indirect modes.

4.9.2. Telemetry Constraints

The scientific telemetry contains the scientific data collected during an observation by the payload instruments, including scientific housekeeping data necessary for the completion of the scientific analysis. Additional engineering housekeeping data which are available to the user are produced but not discussed here as they are part of the mission overheads.

Data rates available to instruments

All observations require the use of the onboard tape recorder (Tape Recorder Unit, TRU) for data storage. The TRU may be programmed at five maximum data rates. Only the following two rates (including a 5% margin) will be available to the user:

TRU SPEED = Default : 60 kbit/s

TRU SPEED = High : 100 kbit/s

4.9.3. Limitations in the use of High TRU SPEED

To ensure complete support to the satellite the mission requires that outside ground contact the tape recorder is always in use at least to record the engineering housekeeping. Only data

⁸Contribution by R.C. Butler and L. Piro

rate = Default ensure this constraint is automatically respected without tape speed changes. Consequently the High data rate can only be allocated for a limited period during each orbit. The maximum time per orbit for which the High TRU SPEED is available is about 55 minutes, which is consistent with the visibility of a source at low declination. Continuation of the observation during the part of the orbit in which the high tape speed is not available, even though the source is not eclipsed by the Earth, is not guaranteed.

4.9.4. Selection of Data Collecting Modes

The default DCM's and TRU speed allow the use of direct modes of NFI without any significant loss of instrument packets for source fainter than about 300 mCrab (the overall telemetry allocation in such case is about 35 kbits/s).

When the overall bit rate becomes greater than 60 kbit/s (that happens for a Crab-like source with a flux half of the Crab) the telemetry is saturated and the loss of data packets becomes substantial. This will produce instruments' data stream with gaps, that may affect temporal analysis of variable sources. The temporal distribution of these gaps will be known post launch.

For such strong sources the observer should then select the DCM's, TRU speed and active instruments according to the main scientific goal. A decisional diagram is presented in fig.4.9.1 to help the observer. A finer tuning of the telemetry allocation (of the order of 20-30 %) - which is not illustrated by this general diagram - can be obtained choosing different options of direct modes or selecting the number of active units of MECS to 1 or 2.

We point out that it is possible to change the instrument settings during the pointing period, so to allocate the available telemetry to different instruments in different part of the observing period (see SA1).

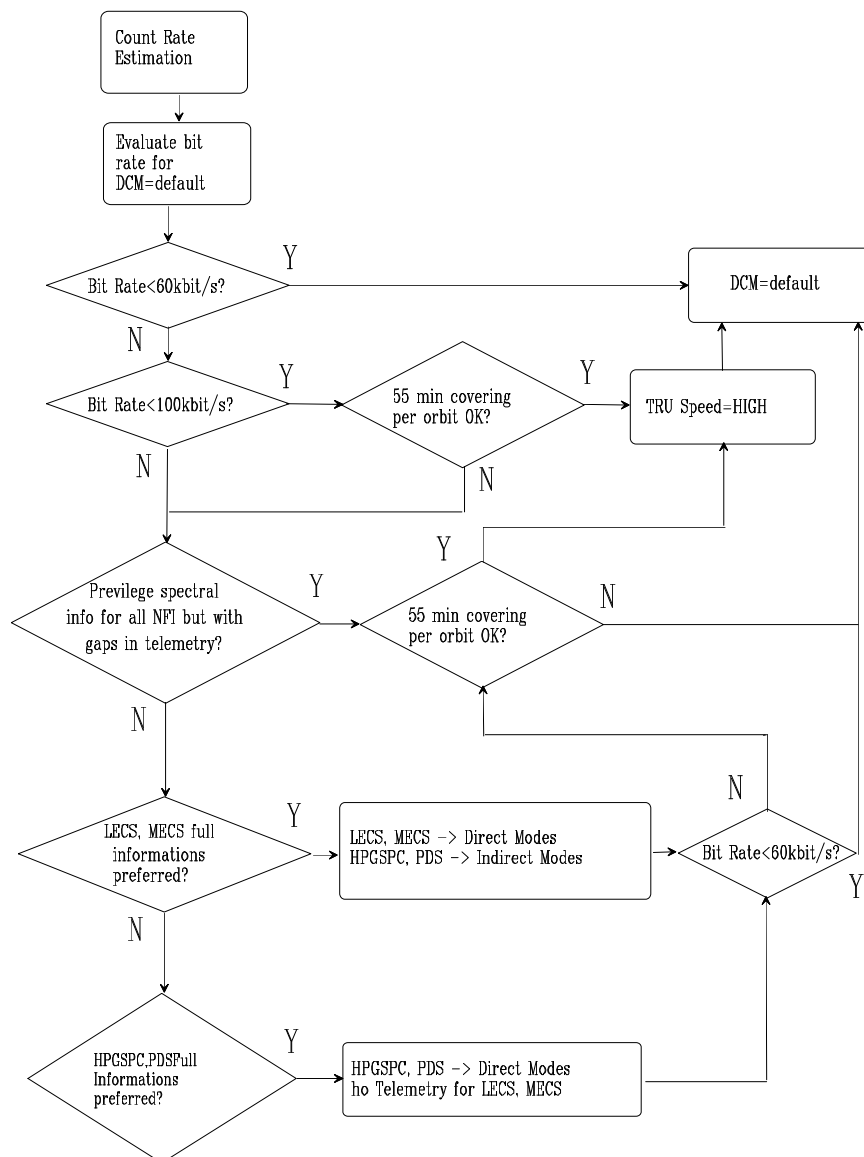


Fig. 4.9.1

4.9.5. Computation of the telemetry rates

Direct modes

The procedure to compute the telemetry bit for direct modes is as follows:

- 1) Compute source count rate n (using figures in instrument sections or tool available for count rate estimation described in Sect.7)
- 2) Compute total count rate TCR adding the background and other contributions to the count rate (such as calibration source). These values are listed in each instrument section.
- 3) Compute the bit rate according to the formula

$$\text{BitRate} = \text{FixBitRate} + C * TCR$$

where *FixBitRate* is the constant Bit Rate (not dependent on the selected DCM) due to HK and C is the number of kbits per event corresponding to the selected DCM

Indirect modes

For indirect modes the telemetry rate does not depend on the source intensity, but only on the indirect mode chosen. The computation of the telemetry rate is therefore very simple:

$$\text{BitRate} = \text{FixBitRate} + \text{BitRateIndirectMode}$$

5. Ground Operations and Data Analysis⁹

5.1. Introduction

The SAX Ground Support System (GSS) provides the support to the SAX Mission from ground during all the project phases. It is in charge of the SAX spacecraft management as well as of SAX data retrieving, storing, analysing and dispatching to the Astronomical Community. The GSS is composed of three main elements:

- The Ground Station;
- The Operation Control Centre (OCC);
- The Scientific Data Centre (SDC).

The Ground Station is located at Malindi/Kenia (3.14S latitude, 40.05E longitude). It is the real communication channel with the spacecraft assuring a single telemetry link of about 11 min every 103 min orbit (indeed 103 min is the approximate time span between a pass over Malindi and the next). During each SAX pass the Ground Station pursues the following main activities: i) telecommand up-linking, ii) mass memory downloading, iii) spacecraft doppler and ranging, iv) On-Board Time - Universal Time Clock (OBT-UTC) synchronization. Besides the S-band antenna and its equipments for Space-earth communications, the Ground Station is provided with a redundant Station Computer (STC) and a Data Relay System (DRS) in order to handle communication with the Operation Control Centre (OCC), which is at Nuova Telespazio Rome 2 (Italy), by means of an INTELSAT V channel. Telemetry retransmissions to Rome are performed on completion of each link and involve files hosting housekeepings, scientific data, OBT-UTC synchronization couples and spacecraft doppler/ranging measurements. In case of the international channel failure the Ground Station is able to store a data volume covering 10 telemetry links as well as to pursue an autonomous contingency spacecraft management.

The core of the SAX satellite management is the Operation Control Centre (OCC). OCC assures functions such as telemetry processing and filing, telecommand generation and validation, orbit and attitude reconstruction, planning of activities, scientific telemetry archiving and quick inspection.

OCC is composed of the following four systems:

- The Spacecraft Control System (SCS);
- The Attitude and Orbit Control System (AOCS);
- The Orbit Determination and Dynamics System (ODDS);
- The Scientific Operation Centre (SOC).

SCS is mainly involved with telemetry and related data retrieving from the Ground Station as well as with telecommand sequences creation for uplink by the Ground Station. Concerning retrieved data, ranging and doppler measurements are passed by the SCS to the ODDS which is in charge of the spacecraft orbit reconstruction and propagation. ODDS assures, as well, the orbital event time prediction such as the link start/end times or the precise tag of the SAX entering/exiting from the South Atlantic Geomagnetic Anomaly. AOCS is the OCC system devoted to SAX attitude reconstruction using as input data acquired by the on board star and sun sensors and transmitted to ground as part of the SAX

⁹ Sect.s 5.1,5.2,5.3 Contribution by L. Salotti and M. Trifoglio

telemetry. AOCS is in charge of the attitude manoeuvres scheduling and validation against the spacecraft constraints.

SOC is the scientific terminal inside the OCC. Here the scheduling of the scientific instrument activity receives its final definition and the SAX scientific telemetry is archived and quickly inspected. A data volume corresponding to approximately seven days of SAX scientific activity are stored by orbit in the dedicated mass memory as soon as they are received from the Ground Station. Once-twice per day, the the Observing Period/Observation structure (sect 5.4.1) is worked out and made available to SDC where the telemetry packets are joined to attitude reconstruction and orbit data.

SOC supports limited facilities for the scientific telemetry inspection by the duty scientist team; they are mainly devoted to instrument performance assessment and WFC image deconvolution for transient source detection and localization.

Telemetry data are transferred to the SDC within one day from their receipt at the SOC. After a time lag of one week they are definitely removed from the SOC.

The Scientific Data Centre (SDC) is the core of SAX science. It has been conceived as the spot where i) all the SAX telemetry is archived, ii) Observation Proposals by Guest Observers are collected, iii) Guest Observers can be supported in analysing data, iv) the SAX Mission Plan is assembled and approved, v) the standard SAX data analysis tools are collected and kept updated and vi) SAX data products are built and archived. In addition SDC creates and dispatches the SAX Final Observation Tapes (FOT) together with SAX documentation, calibrations, analysis tools, newsletters ('SAX Notes'). It is physically located at Nuova Telespazio Rome (Italy) and electronically reachable through Internet and DecNet/SPAN. A LAN links the SDC with the SOC. Functionally speaking the SDC is divided in two components: the Mission Support Component (MSC) and the Scientific Analysis Component (SAC) yet a physical division does not exist with the two components lying in the same rooms and being managed by the same staff under ASI responsibility.

At SDC telemetry is supplemented by Reconstructed Attitude and SAX spacecraft orbital parameters and by OBT-UTC synchronization information. Considering that SAX produces a data volume peaking to one Gbyte per day, it is foreseen that the overall archived data volume amount to well in excess of 750 Gbytes after a two years nominal mission lifetime. Telemetry shall be stored into the SAX Mission Archive as soon as it reaches SDC-MSC from SOC, i.e. approximately one day after their first reception on ground. An exception to this rule is represented by attitude and spacecraft dynamics information which follow different reconstruction frequencies. A relational database addresses the archive contents providing additional information to data file names/paths such as pointing sky coordinates, start/end observation times, Data Collecting Modes etc. Data are extracted from the SAX Mission Archive in order to create the FOTs or when the SDC-MSC telemetry quick look analysis facilities are run.

The following sections introduce the reader to the observation proposal preparation and sketches how proposals and observations are handled at SDC and OCC from receipt of proposals to execution of individual observations, and which data products and software are provided

5.2. Proposals

An Observation Proposal consists of a set of information logically divided into the following

5 groups (details are given in the "Announcement of Opportunity (AO1) for SAX Observing Program"):

- *General Information on proposal*: the set of general data related to the proposal such as Title, Date, PI Name and Address, FOT Media and density and so on. Each Proposal must contain just one Proposal Information set.
- *Pointing Information*: the set of information regarding an Observing Period such as Target Name and Coordinates, etc.. There must be one set of Pointing Information for each pointing in the proposal.
- *Instrument Information*: the set of information regarding a single observation, such as the Instrument Code, the Observation Duration, the Data Collecting Mode (DCM) and the other similar instrument parameter setting. There must be as many set of Instrument Information as many are the instrument settings in each pointing.
- *Additional Information*: the set of information which the user would add to better describe the operations connected with his proposal, in particular time constraints specification and observing plan for TOO.
- *Scientific justification* (this not inserted in the database).

As stated in the AO, proposals must be submitted to the SDC-MSC by normal mail and electronic mail. In this respect paper Proposal Forms are enclosed to the AO, while electronic Proposal Forms can be obtained by SDC-MSC over the networks.

5.3. Mission Planning and Schedule

Being SDC-MSC the collecting point for SAX Observation Proposals, the Observation Proposal Database is the structure that keeps trace of all submitted proposals. Each proposal submitted to SDC-MSC is inserted into the Observation Proposal Database having assigned a 'global status' which accounts for both the state/history of the proposal. Moreover, to each pointing contained in the proposal a 'pointing status' is assigned which specifies the state/history of the concerned pointing and of the related FOT creation procedure.

At SDC-MSC, a number of interactive tools are available to support the Time Allocation Committee (TAC) for what concerns the feasibility of the Observation Proposals with respect to astronomical and operative constraints.

Given a target and a date, **the Target Observability Tool** returns:

- the minimum Sun Aspect Angle at the chosen date, i.e. the minimum angle between the Solar Array vector (the X-axis) and the Sun vector having the target centered in the NFI/WFC Field of View; note that, due to the SAX instrument arrangement with NFIs and WFCs both perpendicular to the Solar Array vector, this figure is independent on the chosen instrument type;

- the angle between the target and the Sun vector;
- the angle between the target and the Moon vector.

The **Target Visibility Tool** helps to figure out how a proposed observation can be performed maximizing the efficiency. In details, this tool computes the time per orbit during which a given target is eclipsed by the Earth as well as the time per orbit during which the SAX spacecraft is embedded into the South Atlantic Geomagnetic Anomaly. Both parameters are extracted considering propagated average orbital elements. In this way it can be estimated the number of SAX orbits needed to obtain a given source exposure. Inputs are the target coordinates, the instrument type (NFI/WFC) and the date at which the estimates must be performed. The rationale for the inclusion of the instrument type is that the target is considered 'visible' by an instrument when the earth limb+atmosphere disappears completely from the instrument Field of View and viceversa 'invisible' when the limb grazes the instrument Field of View.

Finally, the **Sky Map Drawing Tool** provides complete all sky visions highlighting accessible regions at a given date by a given prime instrument type (NFI/WFC). This drawing is accomplished taking into account the Sun constraint and adding up the instrument Field of View width. The Sun and Moon disks are traced while major planet positions are marked. Furthermore, it will be possible to position a target coordinate couple on the sky and to fix the instrument Field of View. In this case, the not prime instrument accessible regions are displayed.

All the Science Pointings (SP) Observations approved by the TAC are extracted from the Database and included in the Mission Plan File (MPF). Before transferring the MPF to the SOC, it is possible to add Slow Scan Manoeuvre (SSM) observation requests (SSM). At any time, a Contingency Scientific Request File (CSRF) can be prepared and sent to SOC to cope with urgent cases (e.g. TOO).

SOC, which receives from the Scientific Data Centre (SDC) an unordered observing plan covering a time span of approximately six months, is in charge of producing an ordered sequence of instrument operations and spacecraft pointings to be passed to the AOCS team for validation and finally to SCS for translation in telecommands to be uplinked by the Ground Station. This task is accomplished in two steps.

Firstly, the Long Term Scheduling orders all the SAX Mission Plan observing requests considering average orbital parameters and event durations (such as the South Atlantic Anomaly passings and the source eclipses by the Earth body). Any Observation which is rejected at this stage is included in the Rejected Requests (RR) file, which is transferred to SDC-MSC and submitted to the TAC for approval.

The Long Term Plan (LTP), on output from the first step, is processed by the Short Term Scheduling which creates, with a few day frequency, the Short Term Plan (STP), which are essentially refinements of LTP portions spanning a week. Short Term Scheduling take benefit of the improved knowledge of the orbit and of the power budget elements. The second step completes with the telecommand sequences generation, which involves collection of timelines and Payload Operation Plans (POP) from SOC together with Attitude

Operation Plans (AOP) from the AOCS.

5.4. Data distribution¹⁰

SDC/MSD will be in charge of distributing all relevant data and information to SAX Observers. These data and information include the following :

— **SAX observational data**, i.e. the science and housekeeping data collected by the SAX instruments and/or the SAX Ground Station (e.g. ranging data), and pre-processed at the SAX OCC (e.g. for attitude and orbit reconstruction). These data will be delivered to the Observer in the form of a **Final Observation Tape (FOT)**, as explained here below.

— **calibration data**, describing the instrument performance as necessary for the analysis of the observational data. In order to ensure that the Observer can always access the most up-to-date set of calibration data, these will not be distributed along with the FOT, but made available for network retrieval.

— **SAX software**, necessary to access the FOT data, do SAX-specific reduction and processing, and interface with the major data analysis packages. This software, developed in the SAX Institutes and integrated care of SDC/SAC, will be portable to the major operating systems. It is described in section 5.5, and will be made available to Observers for network retrieval.

— **SAX documentation**, assembled at SDC from inputs supplied by the SAX Institutes, will also be made available for network retrieval (as explained below) in Postscript format. The documentation will describe the SAX software, the calibration data and technical notes.

With the exception of FOTs (which will be dispatched to the Observers by post) all other data described above will be **accessible over Internet and Decnet**. The intention is to keep at SDC/MSD an up-to-date archive of calibration data, software and documentation, in such a way that observers can easily retrieve what they need.

Access will be possible at least using **anonymous ftp**. Access via **WWW** is under development.

It is our intention to **maintain a mailing list** of Observers and other interested parties, so that they can be notified whenever any calibration data file or software module is updated in the archive. This way observers can evaluate whether they are interested in the update and retrieve it whenever convenient. An up-to-date master copy of everything will be anyhow kept at SDC/MSD.

For the first AO round the documentation and the instrument matrices for

¹⁰Contribution by L. Chiappetti

simulation and other tools for proposal preparation will be distributed as explained in Annex A

5.4.1. FOT production and distribution

SAX science data will be generated on board by the Data Collection Modes described in Section 4. In addition to science data, instruments and other spacecraft subsystems will also generate a variety of housekeeping (HK) data, inclusive e.g. of the Attitude Reconstruction Data (ARD) generated by the AOCS (Attitude and Orbit Control Subsystem). All these data will be sent to the ground using ESA Packet Telemetry standard, therefore there is a natural "unit" in the data, represented by the original packets.

Additional data, like ranging data, will be generated by the Ground Station.

All these data will reach SAX OCC, where the original packet streams will be extracted from the transfer frames. Some data will be processed there, like ARD and ranging data, used by the relevant subsystem to reconstruct attitude and orbit information, while other data will be available for quick look. All data will finally reach SDC/MSD to be archived on optical media.

The archive (the so called Reformatted Raw Data, RRD) will be the starting point for the production of the Final Observation Tapes to be delivered to the Observers. Only science data, a relevant subset of HK data (inclusive of all instrument HK), reconstructed attitude, orbit and time correlation data, and some ancillary information will be put on FOTs, after some minimal reformatting in order to make access to the data easier.

The Observer will be offered a choice of the type of *magnetic medium* over which the data will be written, and he/she shall indicate the choice in the Observing Proposal Form. The current baseline allows :

- *Half-inch magnetic tapes*, at either 6250 or 1600 bpi
- *4mm* Digital Audio Tape (*DAT*) 90 m *cassettes*, at either 2 or 4 Gbyte per cassette
- *8mm EXABYTE cassettes*.

The following definitions (mutuated, as the name of *FOT*, from the experience of Exosat) are applicable to SAX FOTs, and are worth being noted, since they are used to describe the FOT layout.

- an *Observing Period (OP)* is the time interval spent in stable pointing onto a given target to be observed, or (slew OP) the time interval spent manoeuvring from one target to the next. For extension, Observing Period denotes also all the data pertaining to the given time interval. An OP may be subdivided into *observations*.

- an *observation* is a time interval during which the instrument and satellite configuration did not change. The data belonging to one observation can be analysed together (while data belonging to different observations can be analysed together only if the

instrument configurations are compatible). The following events will constitute observation boundaries : any commanded change in the instrument configuration, any commanded attitude change, other relevant events (like entering Earth eclipse or SAA, *TBV for all instruments*). By definition each instrument will have different observation boundaries.

— an ***Instrument Data Set*** is the ensemble of all data relevant to one SAX instrument, produced during one Observing Period on a target, and during the preceding and following slew OPs. In principle one Instrument Data Set will correspond to a FOT.

Data from the WFCs or the NFIs will be always be put on separate tape volumes, however it is possible that Instrument Data Sets from different NFIs will be placed sequentially on a same tape. Note that data from each of the three MECS units will constitute a separate Instrument Data Set.

Multi-volume FOTs are also allowed in case a single Instrument Data Set won't fit on one volume.

The detailed layout of all data on a FOT will be presented in a separate document. However we present here an outline of how data will appear on a FOT. Note that the software needed to file the data from tape to disk, and to access the relevant data files, will be available at SDC/MSD.

FOT	
	* Tape directory (ASCII, one record per tape file)
	* Orbit file (ASCII, produced at OCC by processing of ranging data)
	* Attitude file (ASCII, produced at OCC by processing of ARD)
	* OBT UTC correlation file (ASCII ??, produced at OCC by processing of OBT packets)
	* Several spacecraft HK files (binary; relevant to one target OP and the adjacent slew OPs)
	*
	Instrument data set #1
	* Instrument directory (ASCII, one record per observation)
	Observation #1
	* Observation directory (ASCII, one record per data file)
	* Experiment configuration file (ASCII, lists the setting of all commandable items for the given observation)
	* Instrument HK file(s), binary, one record ~ one packet
	*
	* Instrument science data file(s), binary, one record ~ one packet
	*
	Observation #2
	
	Observation #n
	Instrument data set #2 and following (if any)
	

The principle is that there is one file per observation per data type. Ancillary data files common to more observations, or to more Observing Periods come in the front. Files are indicated by asterisks in the scheme above.

All files are fixed record length files (the actual record length may differ from file to file, and is usually a function of the original packet size and of the reformatting performed). Each kind of file is stored on tape in blocked format (i.e. more records will be packed in a tape block; all information necessary for unblocking is contained in the Tape Directory). The first step of any analysis will be the **FOT filing**, i.e. recreating on disk the original files with the appropriate record length. Software to do this will be available at SDC/MS, as part of the software described in section 5.5.

While ancillary files will be ASCII, usually readable with Fortran list-directed READ, the data files normally used by an observer will be binary. In order to simplify the decoding software, all fields in a record will be reformatted to either 8-bit bytes, 16-bit or 32-bit INTEGER values, so that no bit field handling will be necessary. Data will be in little endian order (as generated on board, and as handled by Digital Equipment machines at OCC and

SDC, which means that some byte-swapping may be necessary on some operating systems (this is likely to be included as an automatic post-processing step in the FOT filing software). All software necessary to interpret packet data, and to accumulate scientifically useful data structures (photon lists, images, spectra, light curves) will be available at SDC/MSD, as part of the software described in section 5.5.

5.4.2. Calibration data distribution

The responsibility of the calibration of SAX instruments during the flight will rely with SAX Experiment Investigator Teams and by SDC/SAC team, that will have the responsibility to verify instruments' cross calibrations. At launch preliminary calibration data, based on ground calibrations performed by Experiment Investigator Teams will constitute the initial versions of the calibration data files.

During the flight routine calibrations will be performed and the relevant *results* made available to Observers as *calibration data files*.

The calibration data files will describe individual "components" (e.g. quantum efficiency vs. energy, energy resolution, time dependent effects, etc.) of the instrument response and constitute the building blocks from which the observer can generate, in conjunction with the information on instrument setup during his/her observation, the instrument response matrix. Software to do this will be provided in the framework of all other software described in section 5.5.

In order to ensure that the Observer can always have timely access to the latest calibration results, it has been felt more convenient (based also on the negative experience of some previous missions) not to distribute the data together with the FOT, but to make them available for network retrieval. Observers subscribing to an appropriate mailing list will be notified of any update.

Calibration data files will be made available, whenever size allows, in the form of ASCII files and FITS files.

5.5. Software for scientific data analysis¹¹

SAX scientific software, necessary to access the FOT data, will allow any Observer to reduce SAX data in a specific SAX format (XAS) as well as in Flexible Image Transport System standard form (FITS). In this way, SAX observational data will be available and ready for analysis with software packages already existing and popular in X-ray astronomy community, including also "home-grown" software, and anyhow to be selected by each

¹¹Contribution by L. Chiappetti, M.C. Maccarone; sect. 5.5.2 by F. Favata; sect. 5.5.3 by R. Jager

user according to individual taste.

From a general point of view, SAX scientific software will be devoted to the data reduction for all those modes available to the Guest Observers, as announced elsewhere in this handbook. The SAX scientific software will allow to read FOT and calibration data, to do SAX-specific reduction and processing, to accumulate photon lists, spectra, images and time profiles and create instrument response matrices.

Net reduced data are finally ready to be passed to the scientific analysis procedures, i.e. to dedicated packages for spectral, timing, and image analysis. SAX scientific reduced data related to **LECS** and **WFC** instruments are directly written in **FITS format** while data coming from **HPGSPC**, **MECS** and **PDS** instruments are primarily written in **XAS format**. Scientific software related to **MECS** data will also have a part developed via **FTOOLS** producing **FITS** files for uniformity with the LECS data analysis system. The XAS files are directly readable by IDL and SAOimage packages but *format converter* programs can be used to convert them in "plain" FITS format (under a default set of simple conventions). Since different packages use different conventions, it is possible either to write a specific converter according to the target package, or leave the rearrangement according to the specific convention to a procedure within the target package. Compatibility of spectral and response matrices files with XSPEC will be provided. The scientific analysis (spatial, spectral, or timing analysis) can then be performed with the existing packages widely used in the astronomical community (e.g. IRAF/PROS, MIDAS/EXSAS, XIMAGE, XSPEC, XRONOS, IDL, ...).

SAX scientific software (including main programs, library routines, utility tools, related documentation and installation guide) will be available to Observers at SDC/SAC as well as for network retrieval, as explained in previous sections. The documentation, essential to any Observer to use SAX scientific software and data, will mainly include a ***User's Guide*** with commands references and cookbook (this will be the only document necessary to use SAX scientific software programs as distributed); a ***Calibration Data Guide*** with the complete description of calibration data files and of their usage (part of this information may appear in form of Calibration Notes and/or articles in the SAX Newsletters and be later incorporated in the Guide); a ***FOT Manual***, including a description of the FOT layout and with the officially supported modes.

Moreover, for internal use only a ***Programmers Guide*** will be available, with the complete description of library routines, include and reference files, data file formats, compiling/linking procedures, in addition to the programming and documentation rules.

5.5.1. HPGSPC, PDS and MECS data analysis

XAS Scientific software primarily developed in SAX Italian institutes will be used for data analysis of HPGSPC, MECS and PDS.

Software for data analysis of the MECS under FITS/FTOOLS environment is developed by Italian Institutes in close collaboration with ESA/ESTEC to provide a common system

to LECS and MECS. Logical flow of this software and main modules are similar to those described in the next Sect.5.5.3.

The general philosophy used for the XAS development takes into account the following considerations and constraints:

- All the software must be as unitary as possible for all the different instruments onboard SAX (same user interface and similar processing philosophy, although taking into account the different instrument requirements).
- All programs of the XAS scientific software will use a consistent user interface, supporting command line arguments, command files (parameter files) and interactive input.
- No monolithic data pipeline, but a series of standalone programs, directly callable by name, normally communicating through global variables.
- No monitor program. This choice simplifies the maintenance of all the software and avoids recompiling and relinking the monitor when new programs are added. Abbreviations of command names and definition of command procedures (scripts) are left to the user which can use familiar operating system facilities, by invoking commands from system level (as DCL or UNIX shell).
- Portability assured by the definition of a reduced subset of system calls, and their isolation in a Virtual Operating System (VOS) library. Currently, at the SAX Institutes, UNIX/Ultrix is supported; VOS for VAX/VMS, Sun and HP-UX systems are used too, but they are not officially supported. It is planned to add (or replace the existing) official support to AXP/OSF1 on Alpha platforms.
- All high level programs and library subroutines in Fortran77. A layer of C routines is present practically only in the (UNIX version of the) VOS library.
- Reduced SAX data files in FITS and/or in XAS format but with a set of programs to convert XAS files in plain FITS

The data reduction phase includes all the SAX scientific software utilities that are necessary to produce data in a form ready for subsequent scientific analysis, starting from FOTs and calibration data files. Time, energy, and spatial selection, corrections for different instrumental effects, background subtraction, are all tasks of this phase.

FOT filing is the first step of the data reduction phase. FOT filing procedure will recreate from FOTs on disk the original “packet” files with appropriate record length.

Accumulation is the second step of the data production phase. It decodes observation directories, accumulates mainly photon lists and also images, spectra, time profiles (including HK), where appropriate, from telemetry files by selecting data on a proper parameter set (time windows, energy ranges, SAA regions, Earth occultation, ...). Moreover, all the corrections that are going to be unchanged in subsequent processing (position dependent energy correction, energy correction for short term gain instability, ...) should be performed here.

Cross-accumulation allows further selection or filtering on the primary accumulated data (i.e. access to FOT data is no longer required). Cross-accumulation programs are

experiment independent and they mainly deal with list of photons to produce other reduced data structures, such as an image with selection in energy and time windows.

Reduction proper is strictly related to the instrument specific accumulations, and it only depends on experiment specific functions, as dead time correction, background subtraction, point spread function correction, and so on.

Response matrix generation. Programs to generate the response matrix of the experiments onboard SAX, appropriate to the observations under analysis, using calibration data, housekeeping data, and particular instrument settings, will be supplied. Matrices will be supplied either directly or by a dedicated Format conversion module, in XSPEC format.

Format conversion programs convert data from/to XAS format to/from plain FITS (or specific flavours of it, as XSPEC) formats, to analyse SAX observational data with many of the existing software packages. For some of them, as SAOimage and IDL, no conversion is required (and simple auxiliary interfaces are available). Conversion is instead necessary to analyse XAS observational data with MIDAS, IRAF, or XSPEC. A Format Conversion module specific to XSPEC will be developed for instrument response matrices and spectral files.

Some **support programs** to be applied on XAS data files may be available, devoted to several different purposes: access to the file content to show/print header information and/or content of a XAS data file, display data files in graphical form (simple plots, colour maps, contour maps), edit/modify data in a XAS file or in its header, generate time window reading cursor co-ordinates from a time profile plot, convert image co-ordinates to celestial ones, perform algebraic operations, etc.

Last but not least, all programs of the XAS scientific software shall be able to communicate between each other, in the sense that each program is able to access the results of a previous one (programs will be normally running sequentially in the same session), either via files as well as via global variables held in memory. A small package of **environment access** modules will be therefore available to set/modify any variable, perform programmatic access to the environment, save global variables (the latter applies only to UNIX operating systems).

5.5.2. LECS Data Analysis Software

The software system for the analysis of LECS data is being developed at SSD/ESTEC. The aim of the LECS package is to allow the user to go from the FOT to the final scientific analysis. In its current form the LECS data analysis system is strongly focused on the spectroscopic analysis of on-axis point sources for observations made in DIRECT (i.e. fully photon counting) mode. Minimal software support will be available for sources which are strongly off-axis, and no support will be available in the current release for diffuse sources, or for the analysis of SPECTRUM or IMAGE mode data.

In order to minimize the development effort it has been decided to re-use as much existing data analysis software as possible. This allow us to integrate the LECS specific software into an already existing framework, namely FTOOLS. This mean that all the files generated and used in the LECS data analysis are in FITS format. The LECS software is being written mainly in C, with some FORTRAN modules on a SunOS 4.1 platform. For installation, the following external software components are required:

- The core FTOOLS installation including the FITSIO library.
- The XSELECT package.
- SAOimage.
- ANSI C and FORTRAN 77 compilers.

All the calibration data sets are stored as FITS files in a calibration database, All the software modules are accessible at the Unix shell level. The software is documented both at the level of the individual modules (through unix-style *man* pages) and at a global level through a user guide and cookbook. The logical flow of LECS data processing will be:

- FOT reading and creation of the FITS files on disk
- Selection of the observation intervals to be used in the subsequent analysis
- Concatenation of the chosen files
- Linearization, i.e. conversion to normalized energy channels and to RA and DEC
- Data Screening based on parameters contained within the event and HK files
- Extraction of the final products (spectra, images and light curves)
- Response matrix generation
- Scientific analysis

The software modules for FOT decoding, and the selection and concatenation of the observation intervals for further analysis are LECS specific modules. They use as input FOTs and produce a set of FITS files containing event lists, HK parameters, attitude data, ephemeris data and auxiliary information. For each filed observation, a summary output can be obtained to allow the user to select the intervals to be concatonated.

The linearization package is also mainly LECS specific software. It converts from PHA to normalized, or PI, channels (by tracking the calibration source gain and by using calibration gain maps), from spacecraft to UT time (using the supplied file), and from raw

pixel positions to linearized coordinates and then to RA and Dec using both calibration data and spacecraft attitude information. The result is to add columns containing PI, UT, linearized pixel and RA and DEC information into the event file and to create a new FITS HK file containing information in physical units, rather than engineering units.

Data screening is performed by a combination of ad hoc and existing software. In particular, a specific module has been developed to display time series of HK and auxiliary parameters and to interactively select good time intervals (GTIs). Alternatively, existing non-interactive FTOOLS such as *maketime* and associated tasks can be used to create and manipulate GTI files based on pre-defined sets of screening criteria. The selection of events is then performed with the FTOOL *fltime*.

The extraction of data products will be performed using existing tools. This can be performed either non-interactively, using a combination of FTOOLS such as *fselect*, *fhisto* and *f2dhisto*, or interactively through a combination of the *XSELECT* and *SAOimage* packages. The result of the extraction is a spectrum, image or light curve in FITS format.

The response matrix generation module produces a response matrix appropriate to an individual LECS spectrum. It accesses the calibration database to retrieve the required FITS calibration files and produces as output a FITS response matrix.

The final scientific analysis such as spectral fitting and timing analysis can be performed using the *XSPEC* and *XRONOS* packages, or similar, depending on the requirements of the user.

5.5.3. WFC data analysis

The software data analysis system of the WFC is FTOOLS/FITS compatible. The logical flow of the software is:

- FOT reading
- Filter and correct event according to WFC and satellite HK parameters, time and energy windows
- Plot HK parameters
- Reconstruct WFC images
- Analyze image and produce for each X-ray source light curve and spectrum.

It will include a module to simulate WFC observations.

5.6. Archival data

Investigators whose proposal are selected will have proprietary use of their data for 1 year after the receipt of the data or after the first release of inflight instruments' calibrations (if this happens after the receipt of data).

After that period data can be requested to the SDC by sending by mail a request specifying the name and address of the observer, and the tape media (1/2", DAT or Exabyte).

The possibility of implementing procedures for retrieval via network is under evaluation.

6. Guidelines for Core Program Proposals¹²

These Guidelines have been prepared by a study group (Observational Program Working Group), which was appointed by the SAX Scientific Steering Committee. They are intended for the following purposes:

- a) illustrate the capabilities of the SAX mission in the relevant astrophysical domains;
- b) highlight the scientific objectives which can be regarded as of higher priority for the mission;
- c) outline observational strategies to achieve the scientific objectives;
- d) estimate an amount of observing time that, according to the strategies in c), can be considered adequate.

The way the Guidelines are presented is therefore aimed not only at pointing out for consideration the most outstanding scientific opportunities, but also at offering a reference for the amount of observing time that could be confidently requested. In order to encourage the community to optimize the efforts in pursuing as widely and deeply as possible the primary objectives accessible to SAX, particular emphasis is given to ample range strategies, where a systematic approach, when applicable, is privileged over a fragmentary one.

Although the best attempt was made to encompass the majority of the foreseeable high priority objectives and to suggest appropriate strategies, there is no pretence either of completeness in the scientific objectives that could be envisaged and of uniqueness in the strategies that could be adopted. Hence the interested proponents need not consider themselves bound to the details of the Guidelines, but rather to the concept of the Core Program that they try to illustrate, with which the proposals submitted for the Core Program should be coherent.

In all cases the Core Program proposals must contain both a detailed scientific justification and an observational strategy. That is, in no case this requirement could be summarily fulfilled just by a reference to the text of the Guidelines.

Concerning Targets of Opportunity (TOO) observations, which are often mentioned in the Guidelines along with an approximate estimate of the time that might be reserved to them, the interested proponents are reminded of the policy described in Sect. 2.2.3 of the AO. In particular beware of the fact that for TOO observations to be taken into consideration, special (TOO) proposals must be submitted, even if the source is either a recurrent transient or a persistent source which may undergo important changes in its state of emission, whose epoch of occurrence cannot be precisely predicted. It is also worth repeating here that, while the scientific merit of TOO observations in the context of this mission is well understood, due to the negative impact they will have on the overall observational efficiency, the number of them which should in the end be considered acceptable for implementation will be limited, and in all respects remains to be assessed.

¹²Contribution by G.C. Perola

The total amount of observing time, which obtains as a sum of that attached to the strategies outlined in these Guidelines, equals the time a priori available for the Core Program in about 3.5 years of operation, if an efficiency of 50% is assumed. Although the first AO refers to the first round of 12 months, and most of the programs anticipated in the Guidelines will not be completed within this round, the proponents are encouraged (see Sect. 2.2.2 of the AO) to submit proposals which contemplates the full extension of their program, where a priority list for the implementation is explicitly given. The selected proposals, whose programs will not be completed in the first round, will have, in any case, to be updated and submitted for the next round, with a scientific reevaluation of their case based also on the results already obtained, and taking into account the operational status of the satellite as it will be communicated at the time.

The Guidelines are given separately for five areas, namely:

- 6.1 Compact Galactic Sources.
- 6.2 Active Galactic Nuclei.
- 6.3 Stellar Coronae.
- 6.4 Clusters and Group of Galaxies; Normal Galaxies.
- 6.5 Supernova Remnants; Soft Gamma repeaters.

Throughout these Sections, the observing times given represent, as a rule, net exposures. The exceptions are self-evident.

6.1. Compact Galactic Sources¹³

This area comprises the compact sources in binary systems, subdivided in four categories:

- 6.1.1 Accreting, weakly magnetized neutron stars (LMXRB).
- 6.1.2 Accreting, strongly magnetized neutron stars (HMXRB).
- 6.1.3 Black hole candidates.
- 6.1.4 Accreting white dwarfs (CV) and Supersoft Sources.

When dealing with each one of these categories, reference will be made primarily to pointed observations with the NFI's, aimed at exploiting SAX capabilities with regard to the very wide energy range and the GSPC spectral resolution. Spectral studies of time dependent (aperiodic, quasiperiodic or periodic) signals can be carried out both within the single pointed observation and by means of properly planned repeated pointings. In this respect it must be kept in mind that: the orbital period of the satellite is 90 min, hence SAX is not very well suited for orbit-phase resolved studies of several interesting sources with orbital period of that order (e.g. most LMXRB's and CV's), although they can be performed through an appropriately large number of consecutive orbits; due to the Sun constraints, the sources close to the ecliptic plane will be accessible only for about two months every six: the window broadens with increasing ecliptic declination, very conveniently the Small and Large Magellanic Clouds will be always accessible.

On issues such as, for instance, the spectroscopy of the K emission and the photoelectric absorption of iron and other elements, ASCA is providing important clues for all four categories: these will have to be taken properly into account in orienting the detailed observational strategies to be described in the proposals.

Other opportunities, mainly for long term temporal studies in the 2-10 keV band, are offered by the WFC's. They will allow to monitor changes in the state of persistent sources as well as to detect transient sources. These opportunities are dealt with in the sections:

- 6.1.5 Monitoring and mapping selected regions of the sky.
- 6.1.6 Transient searches and follow-up observations; gamma-ray bursts.

Sect. 6.1.6 deals also with TOO observations for a timely follow-up study of bright non-recurrent transients, and with studies of gamma-ray bursts using the PDS shield. The soft gamma burst repeaters will be treated in Sect. 6.5.

6.1.1. Accreting, weakly magnetized neutron stars (LMXRB)

Accretion powered X-ray binary systems containing a neutron star are traditionally subdivided into high mass X-ray binaries (HMXRB) and low mass X-ray binaries (LMXRB), according to the nature of the mass donating star. The differences in the optical

¹³ Coordinated by M. Salvati and based on contributions by (in a. o.): L. Chiappetti, E. Costa, D. Dal Fiume, F. Frontera, J. Heise, M. van der Klis, G. Manzo, L. Maraschi, G. Matt, J. van Paradijs, A. Parmar, R. Robba, L. Stella, A. Treves, P. Ubertini, F. Verbunt.

and X-ray properties between HMXRB's and LMXRB's indicate that there is a large systematic difference in the magnetic field strength. The rare LMXRB's with a pulsating, highly magnetized neutron star, are dealt with in 6.1.2.

The LMXRB's are conveniently grouped in two families. The high luminosity ones ($L_X \sim 10^{38} \text{ erg s}^{-1}$), in a X-ray colour-colour diagram, are characterized by three spectral branches which form a Z-shaped pattern (hence the name of Z sources). Correlated with their spectral state in this diagram are their fast variability properties, such as quasi-periodic oscillations (QPO) and low and high frequency noise. The less luminous ones ($L_X \leq 5 \times 10^{37} \text{ erg s}^{-1}$, called "atoll" sources) in the same diagram display two spectral states (called "banana" and "island" states), between which gradual transitions take place, and which are correlated with a very recognizable fast time variability behaviour. Many sources in this family are X-ray bursters, and the X-ray burst properties, in particular the duration, are correlated with the spectral state as well.

In the energy band 2-20 keV the continuum of the Z sources can be described in terms of at least two components, one resembling a black body possibly originating from the neutron star surface, the other a comptonized spectrum possibly emerging from the accretion disk. The atoll sources, instead, do not appear to display the black body component. In sources belonging to both families Fe K-shell transition lines, between 6.4 and 6.9 keV, have been detected: their equivalent widths are comprised between 70 and 130 eV, in a number of cases their width has been found to be very broad, $\sim 0.5\text{-}1.0 \text{ keV}$; possible broadening mechanisms include blending of lines from different ionization states, comptonization, Doppler (and possibly gravitational and transverse) shifts originating from the bulk plasma motions in the vicinity of the compact object.

The very broad band of the NFI's on SAX offers the opportunity to better qualify, and to study in detail for a critical comparison with theoretical predictions, the various continuum components and their relative importance and shape as a function of the spectral state. The 8% energy resolution at 6 keV, while probably insufficient to discriminate among different broadening mechanisms of the FeK line complex, should allow to measure, together with the intensity, the width and the energy centroid as a function of the spectral state.

The same pointings devoted to obtain spectral data will also provide long stretches of timing data; these can be used to study the properties of the QPO's and broad noise components over an energy range wider than previously investigated.

For the objectives briefly outlined, a reasonable strategy is that a selection of 10 bright sources be observed, and that each source on average be pointed at 4 times, in order to investigate the dependence of the spectral properties on source state. As an example, a list of sources could comprise: ScoX-1, GX5-1, CygX-2, GX17+2 as representative Z sources, to which one would like to add the exceptional and intriguing CygX-3; 4U1820-30, 4U1636-536, 4U1608-522, GX9+1, GX9+9 as representative atoll sources. Given their brightness, a typical observing time of $4 \times 10^4 \text{ s}$ for each pointing can be regarded as sufficient, for a total of $1.6 \times 10^6 \text{ s}$.

Another feature of LMXRB's, discovered with EXOSAT, is a variety of "dipping" phenomena in the light curves: they consist of irregular reductions in X-ray intensity caused by obscuration of the central X-ray source by material located in a thick, azimuthally structured accretion disk. The improved spectral resolution of SAX compared to previous PC studies may allow the ionization state of the absorbing material to be directly measured through the energy of absorption edges. A target list could comprise X0748-676, X1254-690, X1624-490, X1755-338, X1916-053. Observing each one of these sources for 1 day should allow to sample a range of binary phases. The total observing time would be 2×10^5 s. This time might comprise a sequence of short pointings to monitor the level of dipping activity: in this case, for the long pointings to be implemented on the basis of the monitoring results, they must be requested in a TOO proposal.

Hard X-ray emission extending to the gamma rays is thought to power an evaporative wind from the companion star, with important consequences for the evolution of the LMXRB's and for the formation of binary (and single) millisecond pulsars. On the observational side, during the last several years it has become clear that the X-ray spectra of low-luminosity LMXRB's are much harder than those of the more luminous sources, and in the 10-100 keV range they become comparable to the hard component in the spectra of accreting black holes (see Sect. 6.1.3). A detailed comparison of accreting neutron stars and black holes will make an important contribution to our understanding of the latter. SAX observations would add greatly to the available information, in particular they would increase by at least a factor of 10 the significance of the positive detection of hard X-ray emission from some LMXRB's in the 40 to 400 keV range by the Sigma telescope on Granat. Fig. 6.1.1 illustrates the accuracy on the spectrum of Terzan 2 that could be achieved in 10^4 s with the HPGSPC and the PDS. Good candidates for the study of such hard components are Terzan 2 itself and 1850-087, and a program to observe these sources, for a total of 4×10^4 s, could be proposed.

Soft, bursting transients, which as a class display properties similar to those of persistent LMXRB's, are considered in Sect. 6.1.6 as candidates for TOO observations discovered during the SAX lifetime.

6.1.2. Accreting, strongly magnetized neutron stars (HMXRB)

X-ray pulsars in binary systems are strongly magnetized neutron stars, which are accreting matter typically from a massive companion, although a few cases are known (e. g. 4U1626-67) where the companion is a low mass star. With the exception of the latter cases, they are among the hardest as well as the strongest X-ray sources in the sky and as such they represent a primary target for the wide band spectroscopy which can be performed with SAX. They can be subdivided in two main classes. The first class contains the pulsars associated with Be stars (BeXRP): they have an extremely irregular behaviour, with flux changes by a factor $> 10^2$, believed to be caused by orbital modulation of the mass accretion rate and/or by sporadic mass ejection from the star. The first mechanism is likely to be the cause of the "recurrent" transient phenomenology, with a recurrence time scale of tens to hundreds of days; the second mechanism is likely to be the cause of the "giant" outbursts:

both types of changes can be observed in the same source, as for instance in A0535+26.

The second class contains pulsars associated with early-type supergiant stars (SGXRP), and it can be further subdivided in two sub-classes: sources that are likely to be wind-fed (VelaX-1, GX301-2, 4U1907+09, possibly 4U1538-52), and sources that are disk-fed, through Roche lobe overflow (CenX-3, LMCX-4, SMCX-1). The first sub-class shows periodicities related to the orbital period, the second sub-class shows periodicities which are probably not directly related to the orbital period but to the presence of an accretion disk (similar to the 35 day period in HerX-1).

The pulsar spectra have a complex shape. What can be regarded as primary radiation is usually modelled as a power law with an exponential cut-off,

$$\begin{aligned} E^{-\alpha} & \quad \text{at } E < E_c, \\ E^{-\alpha} \exp[-(E-E_c)/E_f] & \quad \text{at } E > E_c, \end{aligned}$$

with E_c typically less than 20-30 keV, but the physical meaning of E_c and E_f is unclear. Observations with the Ginga satellite have extended to about 10 pulsars the evidence of cyclotron absorption lines, with the energy of the fundamental ≥ 10 keV. The HPGSPC and PDS are very well suited to improve our understanding of the cyclotron processes in pulsars, thanks to their almost constant effective area from 15 up to about 60 keV, and to the resolution of the HPGSPC: a simulation to illustrate these capabilities is given in Fig. 6.1.2, representing a 10^4 s integration of X0331+53 with a hypothetical distribution of the fundamental and three harmonics in absorption.

The pulsar spectra generally show in addition a low energy absorption cut-off and the iron K fluorescence feature, with $EW \geq 100$ eV, two properties that can be studied in terms of amount and ionization of the matter involved.

The spectral properties are known to depend on the pulse phase, on the luminosity and on the orbital phase. The shape of the primary spectral component, with the associated cyclotron features, displays a pulse-phase dependence, related to the structure of the emitting plasma region and to the radiative transfer in a superstrong magnetic field; a luminosity dependence, related to the accretion rate; an orbital phase dependence (in wind-fed SGXRP) related to the accretion rate along the orbit. The absorption and fluorescence features display an orbital phase dependence, in response to the primary beam scanning through an inhomogeneous distribution of matter; as shown by ASCA observations, a wealth of information can be obtained in the case of eclipsing binaries.

The primary goals of a systematic study of this category of objects could then be summarized as follows:

- a) Pulse phase resolved spectroscopy in a sizeable sample of pulsars, accompanied by a systematic study of pulse profile structure as a function of energy. Fig. 6.1.3 shows the sensitivity of the PDS to a cyclotron line, 11 keV wide and centered at 56 keV, on top of the continuum of X0331+53 but with a depth 100 times smaller than in the simulation shown in Fig. 6.1.2: it is seen that a marginal detection is already obtained in 1000 s.
- b) Monitoring of spectral and temporal behaviour as a function of the X-ray luminosity, a

goal which primarily includes the BeXRP's and the recurrent transients in the first place, but also the 35 day high-low intensity cycle in HerX-1.

c) Orbital phase resolved spectroscopy. Orbital periods are found to be ≥ 1.7 day, extending up to about one month, hence this goal is compatible with both the orbital period of the satellite and the minimum width of a typical observational window (about two months).

For a pulsar program to be most effective, from the above it should be apparent that a detailed observing strategy, source by source, must be devised. This program could in fact be most reasonably an ensemble of well coordinated programs under a single heading. For recurrent transients in this class, when the epoch, at which the appropriate intensity level in an outburst is reached, cannot be predicted with the precision required for a time-constrained observation, a TOO proposal should be submitted; a monitoring program might be advisable. New transients of this type discovered during the SAX lifetime will be treated in Sect. 6.1.6.

A rough estimate of the exposure time needed to study a sample of 10 persistent pulsars and a sample of 5 (recurrent) transient pulsars leads to a total of about 3×10^6 s.

6.1.3. Black hole candidates

Out of the nearly twenty known persistent and transient X-ray binary sources, which are believed or suspected to contain a black hole, for about a third the evidence is supported by dynamical estimates of the mass, for the remainder it relies on the combined spectral and temporal characteristics of the source.

Based on their distinct spectral and temporal properties, several source states have been distinguished in accreting black holes, the so-called low state (LS), high state (HS) and very high state (VHS). Black hole spectra show two clear components: a ultrasoft component (much softer than the spectra of LMXRB's), and a hard power-law tail. In the HS and VHS the ultrasoft component is present and dominates the spectrum below 10 keV; the strength of the power-law component can vary independently of the ultrasoft component, over a large range in timescales. In the LS the ultrasoft component is absent. Two of the persistent sources (Cyg X-1 and GX 339-4) are known to switch from the LS to the HS and VHS. In the LS the power spectral density (PSD) of the intensity variations is distributed as a power law with a low-frequency cutoff in the 100 mHz range; such a PSD is also observed in the VHS, but then the low-frequency cutoff is near 10 Hz. The r.m.s. variations in the LS and the VHS are quite large, of order 10%. In the HS the r.m.s. variations are much smaller ($\sim 1\%$), and the PSD does not show a low-frequency cutoff.

A recent result of great interest is that some low-luminosity LMXRB's have been found to show a PSD which is very similar to that of black hole candidates in the LS; thus, not only with respect to their X-ray spectrum above 10 keV, but also to their variability characteristics, low-luminosity LMXRB's are very similar to accreting black holes. This potentially very interesting result should provide a focus of attention for SAX, whose wide energy range encompasses both spectral components.

The ultrasoft component is generally attributed to thermal emission from the accretion disk,

while the hard power-law component, which appears to extend to 100 keV and beyond with a photon index around 1.7 in the single power-law state, recalls the hard spectral component in Active Galactic Nuclei, and probably originates in the vicinity of the black hole itself.

In some of the sources additional spectral properties have been observed, namely: a structure in emission and absorption around 7 keV, which has been tentatively modelled in terms of Compton reflection and iron K absorption and fluorescence associated with the disk (the EW of the emission line is rather modest, though, ≤ 50 eV); and photoelectric absorption at low energies. Both properties turn out to be difficult to model in a simple manner and are variable, in particular the low energy absorption in CygX-1 can vary on time scales of the order of a few seconds. SS433 is a very special case among black hole candidates, in particular the iron fluorescence line is very strong and displays the same duplicity and precessional shifts as the optical lines.

Observing this type of binaries with SAX will allow a very detailed study of all spectral components and features and of their temporal behaviour, simultaneously over the range 0.1 to 200 keV. A systematic approach on each selected source should attempt also to relate the properties of the absorption and reprocessing features to those of the ultrasoft and hard components, in an effort to diagnose factors concurring to characterize the two states.

As Ginga experience has demonstrated, much can be learned in associating physical and geometrical parameters to the observed phenomenology by studying the spectral variations in bright ultrasoft transients during their decay, not to mention that optical follow up studies have led to discover the best candidates yet on the basis of dynamical estimates of the mass. Further interest comes from the recent discovery of superluminal motions in the radio emission associated with two such transients. A TOO program to follow transients of this type discovered during the SAX lifetime will be dealt with in Sect. 6.1.6.

Concerning the persistent sources, the best candidates are CygX-1, GX339-4, LMCX-1, LMCX-3, with SS433 as a special case. For these objects probably the best strategy consists in planning a number of pointings within the time window when the source is accessible. (A complementary TOO program might be considered, for the study of important changes in their spectral state, which could take advantage of WFC monitorings of the Cygnus and LMC regions, see Sect. 6.1.5). It is to be noted that the width of the accessibility window is well suited for orbit-phase dependent investigations of each one of these five sources, and also for a regularly spaced monitoring of the long term modulation in LMCX-3 (199 d), but not of the precessional period in SS433 (164 d). The exposure time for each pointing will depend on the source and the specific strategy adopted for it. The LMC sources are the less bright, with the flux typically a fraction of $10^{-5} \text{ cm}^{-2} \text{ s}^{-1} \text{ keV}^{-1}$ at 100 keV, a level requiring 4×10^4 s exposure for a reasonably good signal to noise ratio. A program devoted to these sources could extend up to a total of 10^6 s.

Two more persistent sources in the Galactic Centre region have been discovered by the Sigma telescope on Granat to possess a hard spectrum up to at least 100 keV, namely 1E1740.7-2942 and GRS1758-258. The spectrum of the first has been modelled as a

comptonized disk, that of the second as a power law, and on this basis both sources have been proposed as candidate black holes. Since they lie in a very crowded region, confusion effects in the field of view of the HPGSPC and PDS must be considered with care, although all other sources in the field appeared in the Sigma observation to be at least 5 times weaker in the 50-100 keV range. The same region should be monitored at length with the WFC (Sect. 6.1.5), hence a wealth of information on intensity, variability and spectral state in the 2-10 keV range should be recorded in that way. At the flux level recorded by Sigma at 100 keV an exposure time of 10^4 s is sufficient for a good spectral measurement. For a total of 5 pointings per source, the time for this program could be 10^5 s.

6.1.4. Accreting white dwarfs (CV); supersoft sources

6.1.4.1. Cataclismic Variables

X-ray emitting accreting white dwarfs are identified optically as Cataclismic Variables. Traditionally, the CV's are subdivided into three groups, in ascending order of magnetic field strength: the (presumably) non-magnetic Dwarf Novae; the magnetic systems called Intermediate Polars and/or DQ Her type objects, where the field is strong enough to enforce polar-cap accretion, but not enough to enforce corotation; the Polars or AM Her type objects, with fields in excess of a few MGauss, and (almost exact) synchronization between orbital and spin periods.

The X-ray luminosities of CV's are typically of the order of 10^{31-33} erg s⁻¹, the Dwarf Novae being the weakest and the Intermediate Polars the strongest ones. Their emission is subject to both periodic and irregular variations. The spectra are complex and variable, and results from ASCA indicate that current descriptions may still be too simplistic. They include: a) A hard component, modelled in first approximation as optically thin bremsstrahlung with temperatures up to several tens of keV. b) A black-body type component with temperatures up to 1 keV. In Intermediate Polars this component is weak or absent; on the contrary, in Polars it can dominate the bolometric luminosity. In the best studied amongst Dwarf Novae, SS Cyg, it appears to be anti-correlated with the hard component. c) The iron K complex emission, with EW as high as 500 eV. d) Photoelectric absorption with N_H as high as 10^{23} cm⁻². This is well established in Polars and Intermediate Polars, and is phase-dependent at least in Intermediate Polars. The above properties, together with the fact that at least two dozen objects are already known with fluxes $\geq 10^{-11}$ erg cm⁻² s⁻¹ in the 2-10 keV range, make the CV's very well suited for spectral and temporal studies over the entire energy band covered by the NFI's.

The capabilities of SAX for an accurate determination of various spectral components are illustrated with simulations in Fig. 6.1.4 and Fig. 6.1.5. In both simulations, corresponding to an exposure of 10^4 s, the spectral parameters adopted are those typical of AM Her, namely a black body with $kT_1 = 46$ eV, a thin bremsstrahlung with $kT_2 = 18$ keV, an Fe line at 6.5 keV (here assumed narrow) with $EW = 500$ eV; the luminosity in the soft component is 70% of the total. In Fig. 6.1.4, $F(2-10 \text{ keV})$ is 7×10^{-11} erg cm⁻² s⁻¹, in Fig. 6.1.5 it is twenty times weaker: in the first (second) case the input parameters are recovered with a 68% error of 0.3 (1.2) eV on kT_1 , 0.7 (3) keV on kT_2 , 20 (98) eV on the line energy and 30 (155) eV

on its EW.

Because of the proximity of the systems which are bright in X rays, in them the accretion phenomena can be studied in great detail at all wavelengths: a multifrequency approach, with either simultaneous or coordinated observations from the ground, is therefore most appropriate for a deep investigation of physical phenomena such as time dependent radial and disk accretion. Unfortunately, though, their binary periods are nearly commensurate to the satellite orbital period, thus making a binary-phase dependent study of their properties a very demanding task to perform.

Dwarf Novae. As a distinctive property, Dwarf Novae undergo irregular outbursts in all wavelength ranges, due to a sudden increase of the matter transport through the accretion disk. During an outburst the X-ray emission is expected to rise with some delay with respect to the optical, as indeed observed with EXOSAT in objects such as U Gem, SS Cyg and VW Hyd: the delay is of the order of 12 hours and reflects the transfer time of a perturbation across the disk. Observing an outburst with SAX would offer a wealth of information on the dynamics and the radiation transfer; such observations, however, will have to be strictly coordinated with ground-based monitoring. However, it cannot at present be guaranteed that a TOO observation could be performed on a notice as short as 12 hours.

A better understanding of the origin of the various spectral components and of the basic cause of the outbursts (mass transfer versus accretion instability) might be gained by monitoring extensively the inter-outburst light curve. A long series (for instance 30) of consecutive observations of one properly selected Dwarf Nova could be made at intervals of one or two days; an optical campaign should be coordinated with the SAX schedule, but the observations need not be simultaneous.

Other goals that can be pursued with SAX include: spectroscopy of the iron K line in SS Cyg (EW ~ 350 eV), and attempts to better establish the case of iron K emission in other Dwarf Novae; a search for rotation periods, that could be discovered directly or be inferred from a QPO-type behaviour; a search for intensity dips in objects like YZ Cnc, where the presence of a stellar wind is inferred from the P Cygni profiles in UV lines.

An observational strategy could concentrate, for detailed spectral measurements, on 5 Dwarf Novae with flux in excess of 10^{-11} erg cm $^{-2}$ s $^{-1}$. A time of 2×10^4 s devoted to each source leads to a total of 10^5 s. Another 3×10^5 s could be devoted to a long term monitoring of one properly selected Dwarf Nova. For follow-up observations of outbursts detected in the optical, a TOO proposal should be submitted.

Intermediate Polars. They exhibit large amplitude optical and X-ray pulsations, with periods ranging from tens to thousands of seconds, which are thought to represent the rotational (different from the orbital) period of the white dwarf. A SAX program should therefore aim to detailed spectral and temporal studies, with particular emphasis on the study of the rotational modulations, whose periods can be much shorter than the satellite orbit; the difficulties for the study of the orbital modulations, however, are the same as with CV's in

general, and imply observing times of the order of 10^5 s. These extended observations will also allow one to search for QPO-like phenomena, which are expected in these objects in relation with the possible simultaneous presence of an accretion disk and a magnetosphere: compared to LMXRB's, here the advantage would be that the rotation rate is known.

Polars. Their emission is modulated at all wavelengths with the binary period, which is thought to be almost exactly synchronized with the rotation period. In the long term "mode" changes occur in the modulation, which are attributed to the switching over of the accretion column from one magnetic pole to the other. Important goals for SAX should be: detailed spectral measurements from 0.1 to 200 keV, with an accurate determination of the shape of the hard component and possible deviations from thin bremsstrahlung, and investigations of time correlations and lags between soft and hard X rays; these properties, besides, could correlate with the accretion mode.

The spectra also display a typically very strong (total EW of several hundred eV) and variable iron line complex between 6 and 7 keV; first ASCA results suggest the presence of both fluorescence from cold or mildly ionized iron and H- and He-like iron recombination; lower-energy recombination lines are also sometimes present. The GSPC energy resolution, while not good enough to directly resolve the iron complex, will permit a rather accurate measurements of its integral parameters, i.e. intensity, centroid energy and width. The contributions from single lines can then be disentangled by assuming a model for the emission mechanisms. This should greatly benefit from the good SAX sensitivity at high energies, which will permit a quite precise measurement of the temperature of the emitting plasma, and the determination of a possible Compton reflection continuum from the matter responsible for the fluorescence.

Concerning an observational strategy, sources with $F(2-10 \text{ keV}) \geq 10^{-11} \text{ erg cm}^{-2}\text{s}^{-1}$ are the best candidates for time resolved spectroscopy. For a rough estimate of the observing time, 5 representative objects in each of the two groups (Intermediate Polars and Polars) could be observed for 10^5 s each, giving a total of 10^6 s. Within this envelope of time, specific strategies on single objects should be devised, not to mention that some weaker sources may be selected for their peculiarly high interest. Ground based optical monitoring coordinated with the X-ray observations will add great value to the programs.

6.1.4.2. Supersoft sources

The so-called "Super-Soft Sources" (SSS) are rather enigmatic objects. According to several authors, they are likely to be accreting white dwarfs which are undergoing nuclear burning on their surface. It cannot yet be excluded, however, that they represent a special category of LMXRB with a very thick and extended atmosphere. Their most outstanding properties are: a very soft spectrum, detected only at energies below 0.5 keV, which can be fitted with a black body of temperature kT within 10 and 100 eV; a bolometric luminosity of the order of the Eddington luminosity for one solar mass; dramatic time variability in several cases.

The LECS would be sensitive to these sources. Although the expected count rate would be about one order of magnitude lower than in ROSAT, in the relevant energy band the LECS

energy resolution is two times better. Unfortunately the *bona fide*, less absorbed members of this class detected so far belong to the Magellanic Clouds or M31, hence are pretty weak for a useful spectroscopic study. It could however be worthwhile to devote 10^5 s to one or two representative members.

6.1.5. Monitoring and mapping selected regions of the sky

The WFC's, with their field of view of 400×2 square degrees FWHM and their angular resolution of $5'$, will be used to survey extended regions of the sky. With their sensitivity in the 2-10 keV range and the energy resolution typical of proportional counters, they will allow to detect a source of about 2 mCrab in 10^4 s and to obtain in this time sufficient spectral information to tell the spectral type or state of a source above 10 mCrab ($1 \text{ mCrab} = 2.5 \times 10^{-11} \text{ erg cm}^{-2} \text{ s}^{-1}$ in 2-10 keV); the sensitivity limit degrades by a factor about two in very crowded regions like, e.g., the Galactic Centre.

The WFC's will be used in two operational modes: the primary mode, when the pointing direction is chosen to fulfill particular WFC objectives; the secondary mode, when the pointing direction is chosen for the NFI's, with the roll angle of the satellite being optimized for WFC observations subject to all other constraints.

The scientific objectives that are envisaged can be subdivided in two categories, namely those concerned with the monitoring of variable known sources, and those aimed at the discovery of transient sources. This section deals specifically with the first one, and the suggested programs which follow will be primarily pursued with the WFC's in the primary mode, but may benefit also from observations in the secondary mode.

As most of the bright and variable Galactic sources are concentrated in the Galactic disk, it is considered of high scientific value that all of it be surveyed during one year down to the sensitivity limit of 2 mCrab. With 10^4 s per pointing, this program requires 2×10^5 s. The same survey should be repeated once in the second and third years, for a total of 6×10^5 s.

Other programs can be foreseen with the WFC's pointing at crowded regions. Among them, of high priority can be considered the Galactic Centre (GC), the Cygnus and the Magellanic Clouds regions.

In the GC region there is a high concentration of variable sources, in particular objects in the LMXRB and BHC categories and the Galactic Centre itself (Sag A). One of the main drives is a deep study of the X-ray burst sources. Well known is the issue of the peak luminosity in strong bursts exceeding substantially the Eddington limit, with fundamental implications on the distance to the GC being less than 8 kpc, or the intrinsic source luminosity being overestimated due to anisotropic emission, while a possible way out is that the known distribution may be biased against sources on the far side of the GC. SAX offers a good opportunity to further address this problem: to obtain a good statistical ensemble of bursts a total observation time of 8×10^5 s seems to be required.

The Cygnus region contains the very bright sources CygX-1, CygX-2 and CygX-3, of the

highest interest for objectives already mentioned in Sections 6.1.1 and 6.1.3. In addition to the pointing included in the Galactic disk survey, it would seem of high interest to obtain several 10^4 s exposures, up to 5×10^4 s/year for a total of 1.5×10^5 s in 3 years.

The two Magellanic Clouds contain a collection of several bright and variable sources of the classes described in Sections 6.1.1, 2 & 3. Several exposures, for a total of 3×10^5 s in 3 years, could be reserved to this program. Their distribution in time can take advantage from the SMC and LMC being always accessible.

For all of these programs, the last three in particular, it is evident that the maximum scientific benefit can be obtained from a well tuned strategic link with NFI programs concerned with variable sources in the respective regions.

6.1.6. Transient searches and follow-up observations; gamma-ray bursts

An X-ray source is classified as transient on the basis of its sudden appearance, very often at a previously source-free location, and limited duration above a minimum detectable flux. They can be subdivided into two categories. The bright transients can reach a peak brightness over that of the Crab and decay in several months; a fiducial decay time scale of 100 days can be adopted as representative; estimates of their outburst rate are rather uncertain, an indicative rate can be adopted of $5 \times 10^{-4} \text{ deg}^{-2} \text{ yr}^{-1}$ above 50 mCrab, corresponding to about 20 transients in one year, averaged over the entire sky: most events of this type do however occur in the Galactic disk. The weak, fast transients last from a few minutes to several hours and are distributed isotropically over the sky.

The bright (pulsar) transients with a known recurrence period were dealt with in Sect. 6.1.2; here we deal with the others. The combination of the WFC's and NFI's on SAX offers a very exciting opportunity to both detect new transients and, for the bright ones of long duration, to study in detail their evolution during the decay. For what concerns the search of new transients, an observational strategy will be implemented for the WFC's in the secondary mode to survey the largest fraction of the sky which will be accessible at any one time down to a few mCrab, in order to maximize the number of bright transients that can be discovered within at most 100 days after their outburst; the same strategy should also provide a wealth of useful data for the weak and fast transients. In addition, for the purpose of increasing the chance to detect a bright transient above 50 mCrab, the possibility to exploit the slew data from HPGSPC, PDS and WFC's is being considered.

For timely follow-up observations of bright transients with the NFI's, it is essential that their discovery be recognized immediately. To this effect a "service" will have to be implemented to ensure a quick look analysis of all the relevant data of the WFC's both in the secondary and primary modes (and of the slew data, if feasible). A TOO observing program with the NFI's would then be inserted in the schedule, according to criteria that will have to do with the brightness of the source and its nature. In order to benefit from this opportunity, a TOO proposal must be submitted, separately for each one of the three classes of bright transients.

The bright transients can be divided into three classes: ultrasoft transients, several of which have been so far recognized as good black hole candidates; pulsing sources with hard spectra, several of which have been identified with Be companion stars; bursting sources with soft spectra, which belong to the LMXRB's. In total about 5 to 10 events per year are expected to be discovered by SAX within 100 days from the outburst.

Ultrasoft transients. They typically start off with a spectrum dominated by an ultrasoft component, which later in the declining phase settles to a very hard power law. In some cases however the spectrum was found to be of the second type already from the start. As new discoveries may represent a substantial addition to the list of good black hole candidates, their detection and precise localization will be of the highest interest per se. The follow-up X-ray observations with the NFI's should allow one to investigate the temporal evolution and luminosity dependence of the various spectral components and structures described in Sect. 6.1.3.

Hard, pulsing transients. The addition of new objects to the known recurrent transients, already considered in Sect. 6.1.2, could make it possible to extend over a wider range the study of the luminosity dependence of the spectrum, pulse shape and pulse period.

Soft, bursting transients. As a class these transients display characteristics similar to those of persistent LMXRB's. While in outburst they offer an unsurpassed opportunity of: i) studying the orbital dips and/or eclipses and the geometry and physical state of the outermost disk regions and the accretion disk corona for varying accretion rates (the case of EXO 0748-67 has demonstrated the potential of these studies); ii) searching for fast coherent pulsations, due to the neutron star rotation, in the low accretion rate regime in which, possibly, the magnetosphere is larger and the accretion more efficiently funneled onto the magnetic poles; iii) studying the characteristics of the outburst decay and the associated spectral changes, and investigating the origin of the persistent X-ray emission detected in several cases at a level of $10^{33-34} \text{ erg s}^{-1}$.

For a target in each one of these classes, the number and duration of the observations, which could be considered acceptable, will depend on the brightness of the source at the time of the discovery. With a provisional expectation of 2 per year per class well above 50 mCrab, and an assumption of 8 observations lasting on average $2 \times 10^4 \text{ s}$ for each source, the time devoted to these objects on a TOO basis could be 10^6 s per year.

Finally, the **gamma-ray bursts**. The PDS shields will be used to monitor gamma-ray bursts with fluence f_g greater than $10^{-6} \text{ erg cm}^{-2}$ in the energy band from 60 to 600 keV; the time resolution (down to 0.48 ms) will allow a detailed study of their time profile. Information on the position in the sky, with uncertainty of $\sim 10'$ or worse, depending on intensity and direction, can also be obtained. On the basis of the first CGRO/BATSE catalog, ~ 60 bursts per year are expected above the given fluence threshold. Furthermore, ~ 10 bursts with $f_g > 10^{-7} \text{ erg cm}^{-2}$ ($f_g \sim 100 f_x$) are expected to fall in 3 years in the FOV of the WFC's and be detected: hence, for these bursts, an independent $5'$ position might also be obtained, along with spectral and temporal information on the X-ray tail of their emission. This program

does not require dedicated observing time, the proponents should therefore provide the scientific motivation and require access to the gamma-ray burst monitor data and to the WFC data for a cross correlation analysis and for the use of the relevant X-ray spectral and temporal data.

Figure captions

Fig. 6.1.1. A 10^4 s simulated exposure with the HPGSPC and the PDS of Terzan 2, $F(20-100 \text{ keV}) = 6.6 \times 10^{-10} \text{ erg cm}^{-2} \text{ s}^{-1}$, photon slope 1.65. By fitting a power law, the slope is recovered with an accuracy of about 1%.

Fig. 6.1.2. A 10^4 s simulated exposure with the MECS, the HPGSPC and the PDS of X0331+53, $F(2-10 \text{ keV}) = 7.4 \times 10^{-9} \text{ erg cm}^{-2} \text{ s}^{-1}$. The spectrum adopted for the simulation is a power law with photon slope 0.47, and a hypothetical distributions of cyclotron absorption lines with an energy of 28 (the fundamental), 56, 84 and 112 keV, a width of 11 keV and an optical depth of 3 equal for the four lines.

Fig. 6.1.3. A 10^3 s simulated exposure with the PDS of the same source in Fig. 6.1.2, around the absorption line at 56 keV, but with an adopted optical depth 100 and 50 times smaller. The residuals after a power law fitting are shown.

Fig. 6.1.4. A 10^4 s simulated exposure with the NFI of AM Her, $F(2-10 \text{ keV}) = 7.2 \times 10^{-11} \text{ erg cm}^{-2} \text{ s}^{-1}$. The parameters of the spectrum adopted for the simulation, and the accuracy with which they are recovered by the fit, are given in the text.

Fig. 6.1.5. Same as Fig. 6.1.4, when $F(2-10 \text{ keV}) = 3.6 \times 10^{-12} \text{ erg cm}^{-2} \text{ s}^{-1}$.

6.2. Active Galactic Nuclei ¹⁴

On account of the spectral and variability properties of AGN, as well as of the SAX capability to measure their flux up to the 100 keV regime or just up to the 10 keV regime, the objectives have been subdivided into four categories as follows:

6.2.1 Bright Seyfert 1 galaxies and QSO.

6.2.2 Bright BL Lac objects and Blazars.

6.2.3 Bright Seyfert 2 galaxies.

6.2.4 Weak AGN.

6.2.1. Bright Seyfert 1 galaxies and QSO.

From a wealth of spectroscopic measurements performed with previous satellites, up to ROSAT, ASCA and the OSSE experiment on CGRO, the spectra of these objects are known to be complex. They can be schematically described as comprising a basic component, which follows a power law with photon slope 1.5-2.0 up to several tens of keV and possibly a break in the 100 keV regime, a much steeper component often referred to as an excess at soft energies (<1-2 keV), continuum and edge features up to the iron K edge due to low and (or) high ionization absorbing gas, at least one emission feature identified as the iron K fluorescence, and finally an excess continuum above 10 keV generally attributed to Compton reflection. Relative to the basic component, all other components and features can be more or less intense. The basic component is known to be generally variable, and the variations recorded so far occur on time scales from a fraction of the hour to months, with a continuum in the power spectral density distribution; the soft excess is also variable, and a still open issue is the degree of correlation in the variations of these two components; the other components and features can also vary in time, although the evidence of variability has been secured so far only in a few objects.

The major open problems in the models inferred from these measurements can be condensed into the two following issues: origin (thermal or non-thermal) of the power law and the soft components; distribution and physical state of the matter involved in the absorption and in the reprocessing of the radiation. Since the incidence of different spectral properties can be linked one to the other in their interpretation (for instance the soft excess and the high energy break; the primary and the reprocessed components of the emission; the depth of the ionized absorption edges and the intensity of the absorbed radiation) and they are subject to variations, the ideal approach for SAX measurements would be of a type where all spectral properties in one object are simultaneously measured over the entire energy band accessible to the NFI, 0.1-200 keV, and more than once in order to study the variations.

When this approach is followed, the most demanding goal in terms of observing time is the high energy measurement, hence only objects brighter than some limit flux should be

¹⁴ Coordinated by G. C. Perola and based on contributions by (in a. o.): L. Bassani, A. Ferrari, H. Fink, P. Giommi, T. Maccacaro, L. Maraschi, E. Massaro, G. Matt, L. Piro, M. Salvati, E. Tanzi, A. Treves, G. Zamorani

considered prime candidate targets. The example shown in Fig. 6.2.1 illustrates the point with a simulated observation lasting 10^5 s of a source with $F(2-10 \text{ keV}) = 2.5 \times 10^{-11} \text{ erg cm}^{-2} \text{ s}^{-1}$ (MCG-6-30-15 in low state). The spectrum adopted for the simulation, shown in this figure together with the residuals of a fit with a simple power law absorbed by the galactic N_H , contains a power law with photon slope 2.0, a soft component with photon slope 3.5, an OVII-OVIII absorption edge with optical depth of unity, an iron K emission line (350 eV FWHM) together with a Compton reflection bump with intensities expected in a 2π reprocessing configuration, a galactic absorption by $N_H = 5 \times 10^{20} \text{ cm}^{-2}$. The lowest flux limit in 10^5 s for a significant measurement above 50 keV would be about $1 \times 10^{-11} \text{ erg cm}^{-2} \text{ s}^{-1}$.

The implicit advantage of long looks, dictated by the high energy part of the spectrum, is the most effective use of the spectroscopic capabilities of the GSPC's on the absorption edges and the iron K fluorescence line, with particular regard to the ionization dependence of their energies and the kinematically and relativistically induced broadening of the line profile (evidence of a substantial broadening, possibly as expected from an accretion disk, is *emerging* from ASCA data). Another advantage, within the natural limits of light curves broken in most cases by the periodic earth occultation of the source, is the possibility to study the short term temporal variations, with particular regard to the cross-correlation between the soft and the hard X-ray components.

An observing program aimed at a thorough study of the properties mentioned could include a sample of about 20 objects. Their selection can be made following different criteria, it should however represent well the widest possible range of luminosities, and take into account the distribution of optical and radio properties, the EUV bump to soft excess connection, the short and long term variability. The total observing time could be 2×10^6 s for one round of observations and another 2×10^6 s for the repeats. The repeats may follow different strategies, for instance only a subsample of the objects could be reobserved more than once, according to criteria based on the properties of each individual object as known to the date from previous measurements.

Coordination with measurements in other wave bands is encouraged, if guaranteed it would add substantial merit to a proposal.

6.2.2. Bright BL Lac objects and Blazars

The BL Lac objects, either radio (RBL) selected or X-ray (XBL) selected, and the radio loud flat spectrum highly variable quasars (blazars) share properties, with regard to their spectra and variability from radio waves to gamma rays, which distinguishes them rather sharply from the class considered in 6.2.1. In particular the rather large number of extragalactic objects detected at GeV energies with the EGRET experiment on CGRO, and identified with objects of these two classes, emit most of their bolometric luminosity at those energies. The peculiarity of these AGN is generally attributed to beaming effects at small angles to the line of sight in a continuum source of synchrotron and inverse Compton radiation. The X-ray spectra of BL Lac objects display a rather wide distribution of slopes,

with a mean value much steeper than in Seyfert 1 galaxies and QSO's; they show evidence of downward curvature (with hints in some objects of a hard tail) and of a correlation with the luminosity (the slope is flatter in more luminous objects, in single objects it tends to flatten when the luminosity increases), which can be interpreted as signatures of the bulk of the X-rays being the high energy tail of synchrotron emission extending from the radio waves. The X-ray spectral slopes of blazars, to the contrary, are distributed in a fairly narrow range and their mean is harder than in BL Lac's, rather close to, and possibly harder than that of QSO's. The dominant emission mechanism in these object could be inverse Compton radiation. The variability time scales range from hours to months. An intriguing absorption feature at about 0.6 keV has been detected in some objects.

It is generally recognized that, for a better understanding of the source (jet) configuration, of the electron acceleration and emission processes, and of the related intensity and spectral variations, it is of great importance to acquire a detailed knowledge of the X-ray spectral properties over the widest possible range and of their variations, and to investigate their correlation with the spectral and variability properties in other relevant bands.

Two major objectives could be pursued with SAX.

a) Determination of the continuum spectrum over the widest possible X-ray band, thus testing similarities and differences between RBL, XBL and blazars as a function of their luminosity. The selection criteria should apply to complete samples and could be a well thought combination of our current knowledge of their X-ray properties and of their properties in other bands. The demand of exposure time, in view of the steepness in the spectra of most BL Lac objects and of the relatively low flux level of the brightest objects in the three categories, is of the order of $(0.3 - 2) \times 10^5$ s per object, and therefore limits the sample of objects to be selected for this objective to about 15 for a total of 2×10^6 s. Another 1×10^6 s in total could be devoted to repeat observations of some of the brightest objects in this sample.

The simulation in Fig. 6.2.2 illustrates the results expected from an exposure of 3×10^4 s of PKS 2155-304 in a high state of flux, $F(2-10 \text{ keV}) = 1.4 \times 10^{-10} \text{ erg cm}^{-2} \text{ s}^{-1}$: flux would be detected up to 100 keV if the photon slope were constant and equal to 2.6 up to that energy, a spectral curvature would otherwise be easily inferred; the figure shows also the accuracy achievable in the measure of the absorption feature at 0.6 keV reported in this object. Fig. 6.2.3 illustrates the simulated results of a 10^5 s observation of an object like Mk 421, with $F(2-10 \text{ keV}) = 2 \times 10^{-11} \text{ erg cm}^{-2} \text{ s}^{-1}$ and photon slope 2.6, where flux is detected up to about 50 keV. Fig. 6.2.4 illustrates a 10^5 s exposure of an object like 3C279, with flux $1 \times 10^{-11} \text{ erg cm}^{-2} \text{ s}^{-1}$ and photon slope 1.7, where flux is detected up to 100 keV.

These long observations can be used to study fast variations. Strictly simultaneous observations in other bands could be arranged for a detailed study of correlations down to the shortest time scales accessible to the SAX sensitivity. If such observations were secured, it would probably be most convenient to arrange repeat observations at a short distance one from the other, in order to trace possible leads or lags in variations occurring at other

wavelengths.

b) The study of long (a few weeks, several months) term variations are likely to provide significant physical insight only if accompanied by flux and spectral measurements in other bands, from radio waves to gamma rays, including VLBI structural determinations at cm wavelengths. This approach requires a substantial coordination effort, and may thus aim to take advantage from the existence of monitoring programs from the ground, like those performed in the radio band with single dish and VLBI measurements, which are more or less regularly carried out in their own right and could be further stimulated by the coordination with the present program. Further advantage should be taken from a close coordination with monitoring programs which are likely to be implemented with the CGRO satellite in the years to come. To be remembered that sources will be accessible to the NFI only within a time window ≥ 2 months every six months, therefore the extended history of one object in other bands accessible from the ground may be essential to the interpretation of the results.

For this objective a sample of objects should be selected for which significant flux and spectral measurements can be secured in 10^4 s, so that in a total time of 10^6 s for instance 12 objects could be observed eight times in two years. Because from the history of these sources very large outbursts are known to occur in all wavebands, part of the time for variability studies could be requested in a TOO proposal.

6.2.3. Bright Seyfert 2 galaxies

Although originally based on optical spectropolarimetric observations of NGC 1068, the idea of a unified scheme for Seyfert 1 and 2 galaxies, where the nuclei of the latter galaxies are thought to be like those of the former hidden by a large amount of obscuring material, has received strong support from medium energy X-ray observations with the Ginga satellite: in a fraction of objects the X-ray spectrum has the slope typical of Seyfert 1 nuclei (perhaps slightly harder, but this could be the result of a selection effect), and is absorbed by a column N_H of order 10^{23-24} cm⁻²; in others, including the prototype NGC 1068, the primary power law component seems to be completely hidden up to the maximum energy explored, and the X-rays, when detected, could be attributed to scattering of the primary radiation or to a galactic disk component made of discrete sources. The iron K line EW can be much larger than in Seyfert 1 objects, in NGC 1068 it is one order of magnitude larger and the profile (BBXRT and ASCA results) is a complex of transitions from cold and ionized iron. From the above the crucial importance follows of spectral measurements extending well beyond 10 keV, to search for and study the unabsorbed part of the primary spectral component, together with measurements below 10 keV down to a fraction of keV to investigate absorption, fluorescence and scattering phenomena, along with the existence of non-nuclear components.

The energy band of SAX is well suited for the purpose and should be exploited in full. In order to achieve a reasonably good S/N ratio in the 100 keV regime, $(0.5 - 2) \times 10^5$ s are needed for the brightest objects in the class. Fig. 6.2.5 illustrates the results expected from a 4×10^4 s observation of the bright NGC 4388, with an "absorbed" $F(2-10 \text{ keV}) = 2.7 \times 10^{-11}$

$\text{erg cm}^{-2} \text{ s}^{-1}$, $N_{\text{H}} = 2.7 \times 10^{23} \text{ cm}^{-2}$, a power law with photon slope 1.65 and an exponential cut-off with e-folding energy equal to 50 keV (the simulation includes a soft component spatially resolved in ROSAT HRI observations, and a galactic $N_{\text{H}} = 2.6 \times 10^{20} \text{ cm}^{-2}$). A reasonable strategy can be suggested in terms of a program of $2 \times 10^6 \text{ s}$ for one observation of NGC 1068 and two observations of the five brightest objects detected with Ginga and photon spectral index about 1.5; the observation repeats would be aimed at discovering the existence of long term variations, which are expected at least in the unobscured part of the primary spectral component, by similarity with the Seyfert 1 galaxies; another 10^6 s program could be devoted to a few more objects, for an extension of the sample aimed at exploring possible correlations of the X-rays with other properties, such as IR and radio flux, galaxy inclination.

6.2.4 Weak AGN (and the X-ray background)

Measuring at due length of observing time a restricted sample of "bright" AGN is expected to yield important information on the complexity of their spectra and on the temporal behaviour of the various spectral components. However that sample would be too small for a statistical evaluation of how the X-ray spectral properties of a population of objects correlate with other properties, such as radio loudness and morphology, luminosity in the X-rays and in other wave bands, optical colours, redshift and so on. This evaluation would impact both on our understanding of the physical conditions prevailing at different levels and type of nuclear activity and emission processes, and on the issue of the AGN contribution to the X-ray background.

The combination of the LECS and MECS instruments offers the possibility to extend to substantially lower fluxes than in 6.2.1-2 the spectral studies in the 0.1-10 keV band. Notably this band encompasses the energy regime where the XRB appears to change slope, from about 2 (below 1 keV, in photons) to about 1.4 (above 2 keV); it is sufficiently extended towards both low and high energies to confirm and extend the current notion of significant spectral differences among populations of objects selected according to different characteristics, and to investigate the incidence of the "soft" excess and the absorption properties.

To establish a strategy, different criteria can be adopted. For instance, if it is required that for a power law the one sigma error on the photon slope (in the range 1.5-2.5) should be not greater than about 0.1-0.2, from Fig. 4.8.6, it turns out that 10^4 s would be sufficient for a source with unabsorbed flux $F(2-10 \text{ keV}) = 1 \times 10^{-12} \text{ erg cm}^{-2} \text{ s}^{-1}$ and N_{H} between 2 and $20 \times 10^{20} \text{ cm}^{-2}$ (simulation in Fig. 6.2.6), that is about 10 times lower than the limits applicable to the samples in 6.2.1-2. Furthermore, if it is required that a difference of 0.1-0.2 in the mean spectral index of two homogeneous samples should be detectable, then, for a gaussian form of their intrinsic spectral index distribution, each sample should contain about 30 objects, and could be smaller if a larger difference is expected. Then a reasonable choice of samples, with F greater than $1 \times 10^{-12} \text{ erg cm}^{-2} \text{ s}^{-1}$ in the 2-10 keV band, could be the following:

- a) About 30 X-ray selected objects, extracted from the Einstein MSS and/or ROSAT surveys.
- b) About 30 objects extracted from a sample of optically selected AGN. Most of them could be selected from the list of bright PG quasi stellar objects.
- c) About 30 objects extracted from a sample of radio selected quasi stellar objects. For a comparison between steep and flat radio spectra, the sample could be incremented to 60 objects, equally divided in the two types.
- d) About 30 X-ray selected BL Lac objects, extracted from the EXOSAT, Einstein and ROSAT surveys.

The four samples together would amount to 150 sources. The total observing time would be 1.5×10^6 s.

Other classes of objects are of interest, and are not explicitly included in the samples above.

e) X-ray luminous ($\leq 10^{43}$ erg s⁻¹) IRAS galaxies, which are not classified as Seyfert 1 or 2 and whose luminosity is definitely greater than in "normal" starburst galaxies. A spectral and variability program on a sample of such galaxies should help to decide the extent to which the X-ray emission is associated with an exceptional starburst activity or with an embedded AGN.

f) Classical radiogalaxies are found to be X-ray emitters over a rather wide range of luminosity, and there are indications that the radio and X-ray luminosities are correlated. This correlation could be investigated over a consistent sample of objects, selected according to spectral and morphological radio properties and to luminosity.

g) Several AGN detected by the Einstein Observatory and by ROSAT exhibit a very steep soft X-ray spectrum: a substantial fraction of them are classified as narrow line Seyfert 1 galaxies. They can display very large amplitude variations, at least in the soft band, on times scales as short as hours. Their medium energy spectrum is often not well established, hence their soft to hard X-ray luminosity ratio is very uncertain. A program could be devoted to observe a selection of these objects several times, to investigate their spectra and variability in the soft X-rays, and, thanks to the MECS energy band, to explore the hard component.

Depending on the size of the samples and the criteria proposed, an observing time of 0.5 to 1×10^6 s could be devoted in total to these three further programs.

Figure captions

Fig. 6.2.1. A 10^5 s simulated exposure with the NFI of a Seyfert 1 type spectrum with $F(2-10 \text{ keV}) = 2.5 \times 10^{-11} \text{ erg cm}^{-2} \text{ s}^{-1}$, fitted with a single power law with absorption. The parameters of the spectrum adopted for the simulation are given in the text. The inset shows the MECS residuals at the iron K emission line.

Fig. 6.2.2. A 3×10^4 s simulated exposure with the NFI of PKS2155-304 in high state, $F(2-10 \text{ keV}) = 1.4 \times 10^{-10} \text{ erg cm}^{-2} \text{ s}^{-1}$, photon slope 2.6, galactic absorption $N_H = 1.3 \times 10^{21} \text{ cm}^{-2}$, and a 0.6 keV absorption edge (optical depth of 0.7), fitted with a single power law with absorption.

Fig. 6.2.3. A 10^5 s simulated exposure with the NFI of Mk 421 in mid state, $F(2-10 \text{ keV}) = 2 \times 10^{-11} \text{ erg cm}^{-2} \text{ s}^{-1}$, photon slope 2.6, galactic $N_H = 2 \times 10^{20} \text{ cm}^{-2}$, fitted with a single power law with absorption.

Fig. 6.2.4. A 10^5 s simulated exposure with the NFI of 3C 279 in low state, $F(2-10 \text{ keV}) = 1 \times 10^{-11} \text{ erg cm}^{-2} \text{ s}^{-1}$, photon slope 1.7, galactic $N_H = 2.2 \times 10^{20} \text{ cm}^{-2}$, fitted with a single power law with absorption.

Fig. 6.2.5. A 4×10^4 s simulated exposure with the NFI of the Seyfert 2 galaxy NGC 4388 with "absorbed" $F(2-10 \text{ keV}) = 2.7 \times 10^{-11} \text{ erg cm}^{-2} \text{ s}^{-1}$. Spectral form and parameters adopted in the simulation are given in the text. The fit is with a spectrum of the same form used for the simulation.

Fig. 6.2.6. A 10^4 s simulated exposure with the LECS and MECS of a weak AGN, $F(2-10 \text{ keV}) = 1 \times 10^{-12} \text{ erg cm}^{-2} \text{ s}^{-1}$, photon slope 1.7, galactic $N_H = 2 \times 10^{20} \text{ cm}^{-2}$, fitted with a single power law with absorption.

6.3. Stellar coronae ¹⁵

Observations with *Einstein*, EXOSAT and ROSAT have established normal stars as an important new class of low-luminosity galactic X-ray sources (with L_x ranging from less than 10^{27} erg/s to a few times 10^{33} erg/s). Stars of nearly all spectral types emit thermal X-rays from the tenuous ($n_e \approx 10^8 - 10^{11} \text{ cm}^{-3}$) high-temperature ($T \approx 10^6 - 10^7 \text{ K}$) coronae that surround their visible surface. Since the internal structure and atmospheric properties of stars change dramatically across the HR diagram, the study of stellar X-ray emission can provide constraints on a number of important physical problems, such as the acceleration of winds in early-type stars, the generation of magnetic fields by dynamo action in late-type stars, the heating and confinement of plasma by magnetic fields, and the changes in stellar surface activity in the course of stellar evolution. Our knowledge of these physical processes is still at a very rudimentary stage, largely as a consequence of the low spectral resolution ($E/DE \approx 1$) and limited spectral range at which most observations were carried out.

Stellar coronae are intrinsically soft sources with temperatures of up to a few keV; their X-ray spectrum is dominated therefore by emission lines which possess, if suitably resolved, great diagnostic potential. However, apart from very few spectra obtained with grating spectrometers on *Einstein* and EXOSAT, our knowledge of stellar coronae spectra is based mainly on observations obtained at moderate resolution by the SSS instrument on *Einstein*, the ME on EXOSAT and the LAC detector on Ginga. Only recently ASCA has obtained good quality medium resolution spectra that, although not resolving individual lines, provide an accurate description of stellar coronal properties, at least for strong sources. ASCA is significantly more sensitive than SAX in the C/S band, the SIS spectral resolution is definitely better above 1 keV, but it tends to become comparable at lower energies and the energy response does not extend below 0.5 KeV. SAX therefore can still provide useful spectral data on a number of stellar coronal sources, especially if SAX observations are selected in a manner as complementary as possible to those of ASCA.

In 10^4 s good quality spectra can be obtained for sources as weak as $10^{-11} \text{ erg cm}^{-2} \text{ s}^{-1}$ in the 0.5-4.5 keV band, not to mention the much weaker fluxes that are accessible just for detection and variability studies. At this flux limit, there are about 50 stellar coronal sources known prior to ROSAT that can be observed at sufficiently high S/N to allow reliable spectral fits. This number is expected to increase to about 250 sources when the final results of the ROSAT All-Sky Survey will become available. Thus, there is no shortage of coronal sources that could be observed spectrally with SAX. The capabilities of SAX for detailed spectral analysis can be illustrated with simulations, based on the thermal line+continuum model of Mewe et al. (version 1990) of a 10^4 s exposure of a source emitting $10^{-11} \text{ erg cm}^{-2} \text{ s}^{-1}$ in the 0.5-4.5 keV band.

The first example, a single temperature plasma with $kT = 0.4 \text{ keV}$ and two values of the

¹⁵ Coordinated by R. Pallavicini and based on contributions by (in a. o.): F. Favata, R. Mewe, J. Schmitt, S. Sciortino, G. Tagliaferri

column density N_H , is relevant for the corona of an early-type star at a distance of 0.5-1 kpc, where a substantial absorption, associated with circumstellar gas or a massive wind, may be present in addition to an interstellar contribution of about 10^{20} cm^{-2} along the line of sight. The two simulations with the LECS alone are shown in Fig. 6.3.1 ($N_H = 10^{20}$) and Fig. 6.3.2 ($N_H = 10^{21}$): in both cases the input temperature, emission measure and N_H are recovered quite accurately, in particular the errors on N_H (16% and 13%, respectively) are sufficiently small to detect significant absorption close to the star despite of its distance.

The second example, a two temperature model with $kT = 0.5$ and 2 keV , is relevant for the corona of an active late-type star, such as an RS CVn binary: N_H was assumed negligible ($<10^{19}$), which is appropriate for a nearby object. The simulations with the LECS and MECS are performed in two extreme cases, where either the low or the high temperature component contributes only one tenth of the total emission measure. Figs 6.3.3 and 6.3.4 illustrate the results of a single temperature fit when the high and respectively the low temperature component dominates. In the first case the fit turns out to be totally unacceptable; with a two-temperature model (Fig. 6.3.5) the fit is much improved, and both temperature and emission measure are recovered quite accurately, those of the low kT component with an error of $\approx 10\%$, those of the high kT component with an error of $\approx 4\%$.

As shown by the simulations (see also Fig. 4.8.4 in particular for the abundances), SAX can provide useful data for virtually all types of nearby stellar coronal sources, including hot stars, WR+O binary systems, active cool stars of all spectral types, RS CVn and Algol-type binaries, dMe flare stars, and a few isolated PMS objects outside star forming regions (PMS in star forming regions are typically too weak for spectral analysis with SAX). However, the two main topics for which SAX is most likely to give a substantial contribution, even after completion of the ASCA mission, are the following: a) observation of eclipsing binary systems; b) time-resolved spectroscopy of flare-like events.

6.3.1. Eclipsing binary systems

Stellar coronae are extremely inhomogeneous sources in which a variety of different structures in different temperature regimes are likely to coexist. This is suggested by a number of results from *Einstein*, EXOSAT and ROSAT, as well as by spatially-resolved observations of the solar corona. Disentangling the temperature and spatial structure is fundamental in order to construct models of stellar coronal features and for understanding the heating mechanism. This is not an easy task, since stellar coronae are point-like sources whose emission results from the integrated contribution of a number of different structures. Direct information on the spatial/temperature structure of stellar coronae is best obtained from spectral observations of eclipsing binary systems at different phases. RS CVn eclipsing binaries are ideally suited for this study, since they are strong coronal sources, have periods of a few days and have a sufficiently hard spectrum for a differential analysis of the light curves in the LECS and MECS. Several candidates are already known, such as AR Lac, Algol and TY Pyx. Another interesting case is YY Gem, the only nearby eclipsing system among M dwarfs. AR Lac is particularly interesting; it is formed by a G2IV primary and a K0IV secondary separated by about $9.8 R_\odot$ and orbiting each other with a period of 1.98 d. This eclipsing binary has been observed by *Einstein*, EXOSAT, ROSAT and ASCA, and in

all cases evidence was found for both compact and extended coronal components. However, the interpretation of results obtained with different satellites varied considerably; in particular, EXOSAT did not find evidence for an eclipse in the ME band (which was interpreted as evidence in favour of an extended high-temperature component embracing the entire system), while the eclipse was seen by ROSAT and ASCA in all energy bands including the 2 to 8 keV ASCA band. Observations with SAX over the entire range 0.1 to 10 keV, preferably over more than one orbital period, can provide a very detailed mapping of plasma at different temperatures in this (and other) binary systems.

6.3.2. Time evolution of flares.

Flare-like brightenings (with durations from tens of minutes to several hours) are a common feature in stellar coronae emission. They occur frequently in active stars, like dMe flare stars, RS CVn binaries and PMS objects. These events resemble flares on the Sun, but on a much larger scale (up to 10^4 times the largest solar flares). These events are likely to be produced by energy release through magnetic field reconnection, but the detailed physical mechanism remains elusive. Spectral studies of the time evolution of flares (including the temperature and emission measure evolution) provide essential data for comparison with reconnection models and hydrodynamic calculations of the time-dependent evolution of magnetically confined structures. Large flares on nearby dMe stars and in RS CVn binaries are bright enough to allow time-dependent spectroscopy with SAX. In addition, a long (several hours) continuous monitoring of these sources by SAX will allow also the acquisition of high quality spectra of the quiescent emission (useful e.g. for abundance determinations), and the search of low-level variability such as that expected from "microflaring" activity.

There are several sources that could be suitable for this type of studies. The most promising are non eclipsing RS CVn binaries like UX Ari or HR 1099, since they are strong sources and their flares are typically long-lived (several hours). Other suitable candidates are M dwarf flare stars, which although intrinsically weaker, are typically at much closer distances (a few parsec) and have very high flaring rates (typically several flares per day). Flare stars like UV Cet, EQ Peg, AD Leo, Wolf 630, BY Dra, etc. are all nearby sources that can be observed profitably with SAX, although in these case the low orbit of the satellite, and the subsequent data gaps, may cause problems for the observation of short-lived events.

6.3.3. Observing program strategy

It should be clear from the above considerations that a strong stellar program with SAX should include a few selected examples for each class of stellar coronal sources, comprising early-type stars, WR+O binary systems, active late-type stars, RS CVn binaries, and dMe flare stars. However, in order to maximize the scientific return of SAX also in comparison with ASCA, it is recommended that efforts are concentrated on those scientific objectives for which SAX promises to provide a most fruitful and unique return in terms of long standing results. The large bandwidth of the SAX C/S (0.1 to 10 keV), together with the good spectral resolution but limited sensitivity, suggests to concentrate the efforts on programs that require a continuous monitoring of the sources, from several hours to a few days long, and on time-resolved spectroscopy of flares. The bandwidth larger than that of

ASCA at low energies may allow a more precise determination of the multi-temperature structure of stellar coronae, while flares are unique events with large variations from flare to flare. In particular, the observations could aim at the following objectives:

- a) To determine the spatial/temperature structure of coronae through the observation of eclipsing binary systems (both RS CVn and WR+O binaries) for the purpose of obtaining phase-dependent observations of the quiescent emission for at least one entire orbital period; covering more than just one period will help disentangle structural from intrinsic variability in sources which are often highly variable in X-rays. A mean four day long observation of each one of four systems would amount to a total net exposure time of 7×10^5 s.
- b) To study the time evolution of flares in M dwarfs and non eclipsing RS CVn binaries. The samples could comprise 10 sources, each to be observed continuously for about 20 hours, in part simultaneously with ground based optical and radio observations. The total net exposure time would amount to 3.5×10^5 s.
- c) To characterize the spectral properties of different types of coronal sources by observing a few selected objects in each class (O-type stars, single late-type stars, nearby isolated PMS objects like AB Dor, etc.). The sample could comprise about twenty sources, each to be observed for 2×10^4 s. The total exposure time could be 4×10^5 s.

Figure captions

Fig. 6.3.1. A 10^4 s simulated exposure with the LECS of a coronal source with $F(0.5-4.5 \text{ keV}) = 10^{-11} \text{ erg cm}^{-2} \text{ s}^{-1}$, $kT = 0.4 \text{ keV}$, $N_H = 10^{-20} \text{ cm}^{-2}$, fitted with a plasma spectrum with absorption.

Fig. 6.3.2. Same as Fig. 6.3.1, but with $N_H = 10^{-21} \text{ cm}^{-2}$.

Fig. 6.3.3. A 10^4 s simulated exposure with the LECS and the MECS of a coronal source with $F(0.5-4.5 \text{ keV}) = 10^{-11} \text{ erg cm}^{-2} \text{ s}^{-1}$, and with two temperature components, $kT = 0.5$ and 2 keV , the low temperature contributing one tenth of the emission measure. The fit shown is with a single temperature plasma spectrum.

Fig. 6.3.4. Same as Fig. 6.3.3, but with the high temperature contributing one tenth of the emission measure.

Fig. 6.3.5. The simulated exposure in Fig. 6.3.3 fitted with a two temperature plasma spectrum.

6.4. Clusters and Groups of Galaxies; Normal Galaxies ¹⁶

6.4.1. Clusters and Groups of Galaxies.

X-ray observations of Clusters of Galaxies (CG) aim in the first place at a study of the physical conditions and of the metal abundance in the intracluster medium (ICM). From spectrophotometry one can infer the density (n) and temperature (T) of the hot gas component, its metal, in particular the iron abundance (A_{Fe}), the presence of a cold, photoelectrically absorbing gas component and its column density (N_{H}). If the spectrophotometry is spatially resolved, one can infer the space, in particular the radial distribution of those parameters. Through the knowledge of $n(r)$ and $T(r)$ the hot gas mass distribution, $M_{\text{g}}(r)$, can be determined, and, under the assumption of hydrostatic equilibrium, the total gravitational mass distribution, $M(r)$, can be estimated. In the inner regions of a large fraction of clusters the temperature drops due to radiative cooling, and the cooling flow rate can be evaluated. The amount of cold absorbing gas associated with the cooling flow regime can be established. Although the dynamical and evolutionary state of Groups of Galaxies (GG) may be quite different than in CG, similar general statements apply to their observation in the X-rays.

Typical values of the ICM temperature in CG range from about 2 to 10 keV, values below 2 keV are found in the cooling flow regions. In GG the ICM temperatures range from 0.5 to 2 keV. The most prominent iron feature is the 7 keV FeK complex, but at low T a complex of lines, including FeL, becomes prominent below 2 keV. In CG A_{Fe} is about 0.4 the solar value; in GG the metal abundance can be as low as 0.1. The H columns detected so far in CG range up to $3 \times 10^{21} \text{ cm}^{-2}$, and can therefore substantially affect their spectrum below 1 keV. To cover all these spectral aspects simultaneously, the energy band of operation must extend from well below 1 keV up to the continuum blueward of the FeK complex. The full energy band of LECS+MECS is quite appropriate in this respect.

The spectroscopic capabilities of LECS+MECS for a coronal plasma in 10^4 - 10^5 s exposures are illustrated in Fig. 4.8.4. These figures refer to an unresolved source on-axis, and can be applied in first approximation to measurements on an extended source when, taking into account the decrease of effective area off-axis, its surface brightness is higher than the sky plus detector background, a condition adopted in the following considerations on spatially resolved spectroscopy. If that condition is not satisfied, Fig. 4.8.5 obtained with the background within 5' radius on-axis is a better approximation.

For spatially resolved spectroscopy, it must be noted that the angular resolution below a few keV is determined by the detectors and goes like $E^{-1/2}$: a fiducial value of 2.5 arcmin above 3 keV can be adopted, which becomes about 4 arcmin at 1 keV. The effective area of the telescopes drops to half its value on-axis at an angular distance of 15 arcmin. The supporting

¹⁶ Coordinated by G. C. Perola and based on contributions by (in a. o.): H. Bohringer, R. Fusco Femiano, J. Kaastra, D. Maccagni, G. Matt, G. Palumbo, S. Pellegrini, L. Piro, B. Sacco, G. Trinchieri

structure of the ME detector window causes a sharp drop in sensitivity in an annulus between 8.3 and 9 arcmin, and does not otherways interfere significantly with azimuthal averages. The situation is more complicated with the LE detector beyond about 5 arcmin: for extended objects with kT around 1 keV (typically low richness clusters, groups and the early type galaxies dealt with in 6.4.2) a very conservative approach must be adopted, with a few representative targets to be considered in the first year, mainly with the purpose of evaluating the performance achievable.

Consider now how the spatial resolution and the field of view of the C/S match the spatial properties of rich CG as usually described through a radial dependence of the azimuthally averaged surface brightness of the type:

$$(1) \quad S = S_0[1 + (r/a)^2]^{0.5-3\beta},$$

where a is the core radius. Let us adopt for β a fiducial value of 0.7, and for the core radius two fiducial values ($H_0 = 50$), $a = 0.2$ Mpc in XD clusters, $a = 0.4$ Mpc in nXD clusters. The projected core diameter then goes as ($z \ll 1$)

$$(2) \quad \begin{aligned} \text{(XD)} \quad q_{dc} &\sim 2(0.1/z) \text{ arcmin}; \\ \text{(nXD)} \quad q_{dc} &\sim 4(0.1/z) \text{ arcmin}. \end{aligned}$$

If it is required that q_{dc} be at least 4 arcmin (that is approximately one resolution element at 1 keV), an upper limit on the redshift is obtained:

$$(3) \quad \begin{aligned} \text{(XD)} \quad z &\leq 0.05; \\ \text{(nXD)} \quad z &\leq 0.1. \end{aligned}$$

At these limits of distance, the field of view at half maximum of the telescope area would include XD and nXD clusters out to 7.5 core radii.

As a practical rule one can assume that spatially resolved spectroscopy can be performed out to a radius where the surface brightness of the cluster becomes equal to the background (sky plus detector). If it is required that this radius be at least $4.5a$ (or 0.9 Mpc) for XD clusters, and $3a$ (or 1.2 Mpc) for nXD clusters, then the central surface brightness, in the interval 0.5-4.5 keV (this energy interval will be consistently used in the following, also for the luminosities), should be:

$$(4) \quad \begin{aligned} \text{(XD)} \quad S_0 &\geq 8 \times 10^{-13} \text{ erg cm}^{-2} \text{ s}^{-1} \text{ armin}^{-2}; \\ \text{(nXD)} \quad S_0 &\geq 2.5 \times 10^{-13} \text{ erg cm}^{-2} \text{ s}^{-1} \text{ armin}^{-2}; \end{aligned}$$

and the corresponding luminosity should be:

$$(5) \quad \begin{aligned} \text{(XD)} \quad L &\geq 2.5 \times 10^{44} \text{ erg s}^{-1}; \\ \text{(nXD)} \quad L &\geq 3 \times 10^{44} \text{ erg s}^{-1}. \end{aligned}$$

These lower limits can be somewhat reduced for clusters with $z < 0.03$ (XD) and $z < 0.05$ (nXD), for which the field of view at HM contains less than 4.5 and 3 core radii respectively. For instance, at $z = 0.02$, the limits can be reduced by a factor 1.5 (XD) and 2.5 (nXD).

At the maximum distance (3), the flux within a circle of 5' radius, corresponding to the lower limits (5), is:

$$(6) \quad \begin{aligned} \text{(XD)} \quad F &= 1.3 \times 10^{-11} \text{ erg cm}^{-2} \text{ s}^{-1}; \\ \text{(nXD)} \quad F &= 3.9 \times 10^{-12} \text{ erg cm}^{-2} \text{ s}^{-1}. \end{aligned}$$

For the lower of the two flux values in (6), imagine that the central 6' circle (3 core radii) is subdivided into three rings in steps of 2'. The outer ring (4'-6') contains the lowest fraction

of the flux, $8 \times 10^{-13} \text{ erg cm}^{-2} \text{ s}^{-1}$: if $kT = 8 \text{ keV}$, the temperature of this ring can be estimated with about 15% accuracy in 10^5 s (and with better accuracy if kT were lower), hence a 10-15% gradient in T over 3 core radii should be detectable. The same exposure time is required for the higher of the two values in (6), if a similar gradient need to be detected over 4.5 core radii. Furthermore an XD cluster is likely to contain a cooling flow. An appropriate example is A 85 ($z = 0.056$), with $kT = 6.6 \text{ keV}$ and a mass cooling rate of 290 solar masses per year, which emits $5.2 \times 10^{-11} \text{ erg cm}^{-2} \text{ s}^{-1}$ within $5'$: a 10^5 s exposure to this flux is simulated in Fig. 6.4.1, where the isothermal fit shown yields a reduced $\chi^2 = 1.4$. In fact, the spatial resolution well above 1 keV can be used to determine independently the temperature of the gas out of which the cooling flow originates, in this case 6.6 keV: the isothermal fit at this temperature yields a reduced $\chi^2 = 3$, thus indicating that the parameters of the cooling flow could be determined quite accurately. Likewise, for a similar cluster at the same distance, but with a flux and a mass cooling rate both five times lower, the reduced χ^2 would be 1.5, thus suggesting that a cooling flow could be at least detected down to the flux limit in (6) for XD clusters.

As to the available targets, it is useful to note that, for instance, in the catalogue by David et al (ApJ 412, 479, 1993), at galactic latitudes $|b| > 20$ degrees (low galactic N_H) there are about 35 objects out to $z = 0.1$ and $L > 2.5 \times 10^{44} \text{ erg s}^{-1}$. Among them, 15 have $z \leq 0.05$.

By using the spectroscopic capabilities alone, a considerably lower flux limit within $5'$ radius on-axis can be reached for a single temperature and AFe determination. In 10^5 s , this limit is $10^{-12} \text{ erg cm}^{-2} \text{ s}^{-1}$ for an estimate of kT around 8 keV with 10% accuracy, and of AFe around 0.5 with 35% accuracy, and becomes $6 \times 10^{-13} \text{ erg cm}^{-2} \text{ s}^{-1}$ for an accuracy of 15% on kT and of 50% on AFe. These limits correspond to a Coma like cluster out to distances $z \sim 0.3-0.5$. For clusters of low-medium luminosity a $kT \sim 4 \text{ keV}$ is a more appropriate reference value: the flux limit in this case would be 7×10^{-13} (8% on kT and 50% on AFe = 0.5) and $4 \times 10^{-13} \text{ erg cm}^{-2} \text{ s}^{-1}$ (15% on kT). These limits correspond to a XD cluster at $z = 0.05$ with $L \sim (7-11) \times 10^{42} \text{ erg s}^{-1}$ and to a nXD cluster at $z = 0.1$ with $L \sim (3.3-5.5) \times 10^{43} \text{ erg s}^{-1}$.

For small GG, $kT \sim 1 \text{ keV}$, the flux limit for 10% on kT are $10^{-12} \text{ erg cm}^{-2} \text{ s}^{-1}$ in 10^4 s and $2.5 \times 10^{-13} \text{ erg cm}^{-2} \text{ s}^{-1}$ in 10^5 s . These limits correspond to $L \sim 2 \times 10^{41} \text{ erg s}^{-1}$ at 40 and 80 Mpc respectively. However, the determination with about 20% accuracy of both AFe and AZ, if equal to 0.4, requires 10^5 s with a flux as high as $10^{-12} \text{ erg cm}^{-2} \text{ s}^{-1}$; this case is simulated in Fig. 6.4.2, where the temperature fit (first panel) with a pure continuum yields a reduced $\chi^2 = 1.7$, the T and AFe fit with AZ set equal to zero (second panel) yields a reduced $\chi^2 = 1.1$, the T , AFe and AZ fit (third panel) yields a reduced $\chi^2 = 0.9$.

An appropriate strategy for SAX must take into account the new spectroscopic information being collected with ASCA, and try to find a complementary approach, in particular by extending the sample of objects measured and exploiting, when applicable, the sharper PSF at energies around the FeK complex. From the limits described above, one could find such an approach through:

a) A program with a selection of some 15 bright and rich CG for which spatially resolved

spectroscopy can be performed, for about 10^6 s of net observing time.

b) A program with a selection of about 15 CG in the luminosity range 5×10^{42} – 2×10^{44} erg/s, for about 10^6 s.

c) A program with a selection of about 10 GG, including also the Hickson Groups, for about 8×10^5 s.

Some overlap with ASCA observations, especially for the bright objects, should in any case be considered useful for cross-check and intercalibration purposes.

Finally SAX can address what is still an open issue regarding the presence of relativistic electrons in large amount in the ICM. A few clusters are known to possess in the radio band extended emission features which do not appear to be associated with any particular galaxy (halo sources). Depending on the value of the IC magnetic field strength, the inverse Compton emission on the microwave background can lead to a detectable hard X-ray tail above the thermal spectrum. To investigate this issue the three NFI, in particular the C/S and the PDS, are to be used. For a predicted flux level of a few 10^{-6} ph cm $^{-2}$ s $^{-1}$ keV $^{-1}$ in the 30–50 keV region, an integration time of 10^5 s is required. The program should consist of 10^5 s pointings of the Coma cluster and of three other candidates (A401, A2256, A2319). This observing program need not require extra observing time as these objects could well be comprised in the sample of bright clusters selected for spatially resolved spectroscopy.

6.4.2. Early Type Galaxies (E & SO)

The extended emission in early type galaxies is thought to be dominated by the contribution of a hot interstellar medium (ISM), with temperatures around 1 keV, in objects with high L_x/L_o ratio, while at decreasing values of this ratio the contribution of stars and binary star systems is thought to become progressively more important relative to the previous one. An important objective for SAX, thanks to the wide energy band of the C/S instrument, would be that of obtaining new information on the relative importance of the two contributions as a function of L_x/L_o , and on the temperature and metal abundance of the ISM, but the appropriate strategy must take into account the information being collected with ASCA.

Although for the brightest objects ($F > 3 \times 10^{-12}$ erg cm $^{-2}$ s $^{-1}$) within 30–40 Mpc a spatially resolved spectroscopy could be attempted, because the typical temperatures are around 1 keV the conservative approach mentioned in 6.4.1 must be reaffirmed here. In the first year an amount of 10^5 s observing time could be proposed on two–three properly selected objects mainly to verify feasibility.

At present a complementary strategy could be more successfully pursued, for instance a spectroscopic study of a sample of objects with flux, within a circle 5' in radius, ranging from 3×10^{-13} to 3×10^{-12} erg cm $^{-2}$ s $^{-1}$, with the purpose of exploring the widest possible range of L_x/L_o . For objects with $kT = 1$ keV, AFe and $AZ = 1$, the temperature could be estimated with an accuracy of about 10% and the two abundance parameters with an accuracy of about 40%, in 10^4 s at the top of that flux range, in 10^5 s at the bottom. For a total time of

$(5-10) \times 10^5$ s a fairly large sample of objects could be observed, its size depending on a compromise between the distribution in flux and the extension in L_x/L_o that one might be willing to explore.

6.4.3. Late type galaxies (S&I)

The X-ray emission in normal late type galaxies is likely to be dominated by compact binaries and SNR's, with some contribution by stellar coronae and by the hot phase of the ISM. In M31 a large number of the brightest sources have been individually resolved. The X-ray luminosity of these galaxies in the 0.5-4.5 keV band ranges from 10^{38} erg s⁻¹ to a few 10^{40} erg s⁻¹, and appears to correlate linearly with the optical luminosity.

Objectives that could be pursued with the C/S instrument on SAX are of two types: study of individual bright sources in M31; study of a representative sample of relatively nearby galaxies.

In M31 there are a few sources with flux above 10^{-12} erg cm⁻² s⁻¹. Spectral and variability studies could be performed to investigate their properties for a comparison with those of the compact galactic sources. A total time of 1.5×10^5 s could be devoted to this program, to secure at least two observations for each one of three to four sources. Even if already carried out by ASCA, depending however on the results, a follow-up variability study with SAX might still be desirable.

Programs of the second type should aim at a detailed spectral investigation in a representative sample of relatively nearby galaxies, selected according to luminosity and morphology. For bright objects in the sample, with a sufficiently large angular extent, a spatially resolved spectroscopy could be attempted with the MECS, in order to separate the bulge, disk and spiral components. The extension to the medium X-ray energies of the spectral information collected at lower energies, with the Einstein Observatory and ROSAT, would significantly contribute to evaluate the proportion among the galactic source types which are likely to dominate the emission, in particular the proportion between the low and high mass X-ray binaries, in different galaxies and in different parts of the same galaxy.

The integrated flux from objects with $m_B \sim 9$ is about 10^{-12} erg cm⁻² s⁻¹. Down to this limit of flux a significant spectral information up to the FeK line can be obtained in $1-2 \times 10^4$ s. For brighter and extended objects the exposure should be of $5-10 \times 10^4$ s for spatially resolved spectroscopy. Different strategies can be adopted, with a different sample composition. Within a total observing time of 8×10^5 s, a sample of about 20 galaxies with $m_B \leq 9$ could be studied, of which about five could be pointed at due length of time for spatially resolved spectroscopy. The sample should contain also a selection of starburst galaxies; in fact, for this type of galaxies, it might be more scientifically effective to devise a program including also the galaxies with exceptionally high IR and X-ray luminosities referred to in Sect. 6.2.4, e).

In proposing programs of the second type, an up to date comparison of ASCA results with the expectations from SAX must be presented. The rather sharper PSF of SAX around the

FeK line energy, or just the sample complementarity, are arguments that may apply and therefore be properly presented to make the case for acceptance convincing.

Figure captions.

Fig. 6.4.1. A 10^5 s simulated exposure with LECS and MECS of a cluster at $z = 0.056$ with a cooling flow ($A = 85$), $F(0.5-4.5 \text{ keV}) = 5.2 \times 10^{-11} \text{ erg cm}^{-2} \text{ s}^{-1}$ within a circle 5 arcmin in radius (see text for adopted parameters), fitted with an isothermal coronal spectrum.

Fig. 6.4.2. A 10^5 s simulated exposure with LECS and MECS of a Group with $F(0.5-4.5 \text{ keV}) = 10^{-12} \text{ erg cm}^{-2} \text{ s}^{-1}$ within a circle 5 arcmin in radius, $kT = 1 \text{ keV}$, $A_{\text{Fe}} = A_Z = 0.4$, fitted with (a) a pure continuum, (b) continuum and iron lines only, (c) continuum, iron and other metals.

6.5. Supernova Remnants and Soft Gamma Repeaters ¹⁷

Supernova Remnants (SNRs) play a relevant role in supplying matter and energy to the interstellar medium, and in the chemical evolution of galaxies. SNRs can be divided into three categories:

1. Shell-like remnants emit radiation associated with the passage of a shock wave through either the interstellar medium (ISM) and/or the supernova ejecta.
2. Crab-like remnants (also called "plerions", or centre-filled) are objects with a central neutron star dominating the energetics and producing a synchrotron nebula;
3. Other remnants, with neither of the above features, or both.

The study of SNRs at X-ray wavelengths is of vital importance for our understanding of the fundamental physical processes involved, the evolution of the ISM, and their progenitors. The instruments on SAX relevant for SNRs studies are the LECS and MECS, the HPGSPC, and, for the plerions, the PDS as well.

6.5.1. Shell-like SNRs

It is generally assumed that the thermal X-ray emission we observe in supernova remnants is due to the interaction of an expanding blast wave with the surrounding ambient medium. The conditions of the ambient medium can be either those of the local interstellar medium not previously disturbed by the activity of the progenitor star, or those resulting from the interaction between the ISM and a stellar wind.

This is schematically the standard picture for remnants evolving in the adiabatic phase, described by means of a self-similar solution of the hydrodynamical equations of the evolution of a blast wave (phase II). The above scenario also applies to older remnants (phase III) in which radiative losses dominate the hydrodynamical evolution of the remnant. In older remnants the situation is often complicated by the presence of both large and small scale variations in the structure of the ISM (e.g. clouds, molecular clouds, z scale height, etc.).

In much younger remnants (phase I) the scenario is hydrodynamically more complicated: an additional soft X-ray component is present, due to an inward-moving shock (the reverse shock) resulting from the deceleration of the main shock. The reverse shock heats up the material ejected during the supernova explosion, and the resulting X-ray emission is affected by the hydrodynamical behaviour of the reverse shock and by possible enrichment of stellar debris.

From the observational point of view, the interpretation of X-ray spectra of SNR through plasma emissivities in collisional equilibrium points to the presence of two (or even more) components at different temperatures. While this could be expected in principle for very young remnants, a serious problem arises for older remnants. Two effects can yield X-ray

¹⁷ Coordinated by A. Preite Martinez and based on contributions by (in a. o.): W. Brinkmann, A. Ferrari, R. Fusco Femiano, J. Kaastra, R. Trussoni

spectra different from equilibrium spectra:

(i) Non equilibrium. It is well known that in young remnants ionization time scales are longer than the hydrodynamical (HD) time scale. For older remnants in the radiative phase recombination time scales are longer than the HD time scale. In the adiabatic phase the non-equilibrium ionization structure (NEIS) of the remnant will lag behind the ionization structure corresponding to the idealized situation of collisional equilibrium. It should be emphasized that in general under- and over-ionized material can be present at the same time in different regions of the same remnant.

(ii) Non equipartition. If the electron temperature is significantly lower than the mean temperature, the continuum emission should be steeper than in the equipartition case. This point is worth investigating above 10 keV with the HPGSPC.

Discrepancies between observations and model predictions are also expected as a consequence of inhomogeneities in the ambient medium and anisotropies in the explosion. Spatially resolved spectra of young remnants should be obtained to evaluate their relevance.

In historical remnants it is not yet proven where the various components of the spectrum originate (i.e. reverse shock or ISM). With spatially resolved spectra (or images just in Si-K, S-K, Fe-L, Fe-K, and continuum) it will be possible to approach this problem. Bearing in mind that the resolution is about 2 arcmin at the Fe-K energy, this will not be possible for the smaller objects. In the following table we give the flux in 10^{-11} erg cm $^{-2}$ s $^{-1}$ above 2 keV per resolution element (assuming emission from a shell with thickness 10% of radius and a resolution circle of 2 arcmin) and the priority (AA = very high, possible use as calibrator, A = high, B = medium, C = low).

SNR	diameter (arcmin)	F(> 2keV) (F2)	F2/pixel	priority
Cas A	4.1	77.0	22.6	A
Tycho	7.5	15.0	1.32	AA
Kepler	3.5	2.6	1.07	A
SN 1006	31.4	3.9	0.02	A
RCW 86	36.0	6.5	0.025	A
G11.2-0.3	4.2	3.4	1.06	B
RCW 103	9.0	2.1	0.13	B
W49B	3.6	9.1	3.5	B

High-statistics spectral study of the four historical SNRs (Cas A, Tycho, Kepler, and SN1006) should get high priority (AA-A, the highest for Tycho, with an extended observation of this source to search for the hard tail seen by HEAO-A2).

In large, older remnants the SAX MECS could perform a spectral mapping of bright spots. In doing this, one could take advantage of the somewhat better spatial resolution at the Fe-

K line than that of ASCA. The Cygnus Loop, Vela SNR, Puppis A, and IC 443 are targets with the same priority (B).

In summary, an observing program for the shell-like SNRs could be subdivided in two parts. The first devoted to the historical SNRs (with particular regard to the search for a hard tail in their spectrum) for a total exposure time of 2×10^5 s. The second devoted to spatially resolved spectroscopy, for a total time of 4×10^5 s.

6.5.2. Crab-like SNRs

In addition to shell SNR, the SAX mission is well suited to contribute to our knowledge of the "plerion" class of remnants.

As known from the relevant literature (see e.g. Weiler and Panagia, 1980, A&A 90, 269), this class is morphologically shaped by the presence of an active pulsar in the centre of the remnant; the emission is peaked at the centre and is basically related to non-thermal relativistic electrons. The study of these SNR is therefore relevant to the phenomenology of the pulsars themselves.

The standard picture of plerions, as derived from the Crab Nebula which is the prototype of the class, assumes that an active pulsar feeds energy into the surrounding shell ejected by the supernova explosion, under the form of relativistic plasma and, possibly, strong low-frequency electromagnetic waves. This relativistic wind interacts with the shell, and plasma instabilities of various type lead to the release of its energy and momentum in a well defined region a few light-months (up to a light-year) away from the pulsar. Magnetic field and plasma compression enhance locally the non-thermal emission at radio, optical, and X-Ray frequencies. Such region corresponds to the "wisps" of the Crab Nebula and is the source of the central peak of emission, especially relevant at high frequencies. Relativistic electrons of the wind and/or accelerated at the wisp region are then released into the large scale SNR and support its non-thermal emission.

pulsar phase and can be estimated in the order of 10^4 years. Obviously pulsars inside plerions cannot be seen in all cases, but their presence can be inferred from the spectral characteristics of Crab-like remnants in the radio and X-Ray spectral ranges, where the non-thermal relativistic electron component contributes above the thermal components.

In addition to the Crab Nebula, many plerions have been studied in the radio range, and at X-Ray frequencies by the Einstein Observatory and EXOSAT. In particular, EXOSAT observations of MSH 15-52 provided evidence for the presence of a flat spectral component corresponding to the pulsar.

The contribution of the SAX mission in this field will be the study of the extended spectrum of selected plerion candidates up to the highest accessible frequencies, in order to extract evidence of a hard spectral component. Relatively few plerions have well established spectra above 4 keV, and this represents a problem, because the energetics depends upon the slope of the spectrum, which, when the energy range available for the spectral fitting is restricted below a few keV, is very sensitive to the assumed value of N_H .

For plerions with identified pulsars, the time-resolved counts can be folded with the period to obtain the pulsar spectrum itself. In other cases, the overall shape of the spectrum alone, and particularly the presence of a hard component, will disclose the presence of the compact central source.

In the following table a list of possible targets is given, in order of decreasing priority. A rough estimate of expected photon fluxes, based on extrapolations of previous observations, indicates values from 10^{-2} ph cm $^{-2}$ s $^{-1}$ keV $^{-1}$ in the 1 keV range, to 10^{-6} ph cm $^{-2}$ s $^{-1}$ keV $^{-1}$ in the 100 keV range. These values should allow detection and spectroscopy in 10^4 - 10^5 s. The aim would be to obtain the spectrum up to the highest energies using all NFI; there is no hope for spatially resolved spectroscopy, as all plerions (except the Crab Nebula) have small angular diameters.

SNR	IPC (counts/s)	Period (ms)	remarks	priority
Crab	684	33	synchrotron	AA
Vela X	490	89	irregular	A
CTB 109	5.2	6980	binary c.s.	A
MSH 15-52	2.4	150	synchrotron	A
CTB 80	0.17	40	central source	A
G 291.0-0.1	0.22		synchrotron	B
G 74.9+1.2	0.04		synchrotron	B
G 21.5-0.9	0.49		synchrotron	B
3C 58	0.35		synchrotron	B
G 5.3-1.1				C
G 93.7-0.3				C

To the observing program for the Crab-like SNRs a total exposure time of 4×10^5 s could be devoted.

6.5.3. Soft gamma burst repeaters

Unlike the bulk of the gamma ray burst sources, three are known so far to emit repeated bursts, hence are designated as Soft Gamma Repeaters (SGR), and are characterized also by a softer spectrum. Especially after the X-ray identification by ASCA of SGR1806-20, there is wide consensus on their association with SNR, most likely with a neutron star within them. ASCA experience have shown that X-ray observations can be very fruitful, with regard both to the more precise localization obtainable with imaging instruments and to a spectral/temporal study in this band. SAX looks rather well suited for the same purpose, the strategy may combine survey observations at the location of SGR and TOO observations triggered by the discovery of a state of burst activity. A total exposure time of 5×10^5 s could be devoted to SGR observations.

7. Additional informations

7.1. Tools and documentation available through network

7.1.1. AO and Sax Observers' Handbook

These documents are available via anonymous ftp (type in your e-mail address for password) in any of the following computers :

iasax1.ias.fra.cnr.it

or

sax.tesre.bo.cnr.it

or

www.sdc.asi.it

The AO is located in the directory:

/pub/sax/doc/ao1

The SOH is in the directory:

/pub/sax/doc/handbook

7.1.2. Instruments' response matrices, effective area and background files for simulations

Matrices, effective areas and background files of all SAX instruments in XSPEC format are available (in the same sites as before) in the directory:

/pub/sax/cal

7.1.3. Count rate (PIMMS) and visibility (VIEWING)

PIMMS (Portable Interactive Multi-Mission Simulator) is a program to evaluate the count rate.

VIEWING allow users to calculate observing windows of different satellites.

The latest versions of these programs include SAX.

They are available via anonymous ftp on:

legacy.gsfc.nasa.gov

or can be used directly on the XRAY account of:

heasarc.gsfc.nasa.gov

7.1.4. WWW

SAX mosaic pages are available at the URLs

http://www.sdc.asi.it/sax_main.html

and

http://titan.ias.fra.cnr.it/ias-home/sax/sax_main.html

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7.2.3. Help Desk

Questions concerning the AO and the SAX mission can be sent via E-mail to

helpdesk@sax.sdc.asi.it

A. List of acronyms and reference documents

A

AO	Announcement of Opportunities
AOCS	Attitude and Orbit Control System
AOP	Attitude Operation Plan
ARC	Archive
ARD	Attitude Reconstruction Data
ASCII	American National Standard Code for Information Interchange
ASI	Agenzia Spaziale Italiana

B

BCU	Battery Control Unit
BTB	Block Transfer Bus

C

CHF	Command History File
CL	Command Language
CNR	Consiglio Nazionale delle Ricerche
CoI	Co-Investigator
CP	Core Program
CTU	Central Terminal Unit

D

DAWG	Data Analysis Working Group
DRS	Data Relay System

E

EIWG	Experiment Investigator Work. Group
ESA	European Space Agency
ESTEC	European Space Technology Center

F

FAR	Final Acceptance Review
FITS	Flexible Image Transport System
FOT	Final Observation Tape
FTP	File Transfer Protocol
FWHM	Full Width Half Maximum

G

GO	Guest Observer
GOP	Guest Observer Proposal

GRB Gamma Ray Burst
 GRBM Gamma Ray Burst Monitor
 GS Ground Segment
 GSPC Gas Scintillator Proportional Counter
 GSS Ground Support System

H

HK House-Keeping
 HKD House-Keeping Data
 HOLF Historical Observation Log-File
 HPGSPC High Pressure GSPC
 HTML HyperText Markup Language
 HTTP HyperText Transport Protocol
 H/W HardWare
 HW HardWare
 HWHM Half Width Half Maximum

I

IAS Istituto di Astrofisica Spaziale
 (Frascati)
 IFCAI Ist. Fisica Cosmica e Applicazioni dell'Informatica (Palermo)
 IFCTR Ist. Fisica Cosmica e Tecnologie Relative (Milano)
 I/O Input/Output
 IT Intelligent Terminal
 ITESRE Istituto di studio e Tecnologie sulle Radiazioni Extraterrestri (Bologna)

J

K

L

LAN Local Area Network
 LC Local Center
 LECS Low Energy Concentrator
 Spectrometer
 LEGSPC Low Energy GSPC
 LEO Low Earth Orbit
 LT Long Term
 LTP Long Term Plan
 LTPF Long Term Plan File
 LTPG Long Term Plan Generation

M

MECS Medium Energy Concentrator
 Spectrometer
 MIDAS Munich Image Data Analysis System

MIP Mission Planning
 MMI Man Machine Interface
 MP Mission Plan
 MPF Mission Plan File
 MSC Mission Support Component

N

NET Networking
 NFI Narrow Field Instrument
 NFS Network File System
 NIVR Netherlands Agency for Aerospace Programs

O

OBC OnBoard Computer
 OBDH OnBoard Data Handling
 OBT OnBoard Time
 OCC Operation Control Centre
 OD Optical Disk
 ODDS Orbit Determination and Dynamics Subsystem
 OLA Off-Line Analysis
 OP Observing Period
 OPA Observational Proposal Archive
 OPWG Observational Program Work. Group
 OT Observing Time

P

PDS Phoswich Detector System
 PHA Pulse Height Analyzer
 PI Principal Investigator
 PIMMS Portable Interactive Multi-Mission Simulator
 P/L PayLoad
 PMT PhotoMultiplier
 PMA Parking Memory Area
 POP Payload Operation Plan
 PPDU Power Protection and Distribution Unit
 PSF Point Spread Function

Q

QL Quick Look

R

RCS Reaction Control Subsystem
 RRD Reformatted Raw Data
 RT Real Time
 RTU Remote Terminal Unit

S

SAA	South Atlantic Anomaly
SAC	Scientific Analysis Component
SAO1	Announcement of Opportunity (AO-1) for SAX observing time
SAX	Satellite per Astronomia X
S/C	SpaceCraft
SDC	Scientific Data Center
SDC/SAC	SDC/Scientific Analysis Component
SDC/MSD	SDC/Mission Support Component
S/N	Signal-to-Noise ratio
SNR	SuperNova Remnants
SOC	Scientific Operation Centre
SOH	SAX Observer's Handbook
SOP	Short Observation Plan
SQLA	Scientific Quick Look Analysis
SRON	Space Research Organization of the Netherlands (Utrecht)
SSD-ESA	Space Science Department - ESA
SSSC	SAX Scientific Steering Committee
ST	Short Term
STP	Short Term Plan
SW	SoftWare
S/W	SoftWare

T

TAC	Time Allocation Committee
TLC	Telecommands
TLM	Telemetry
TOO	Target of Opportunity
TRU	Tape Recorder Unit
TT&C	Tracking, Telemetry, and Command

U

UOR	Urgent Observation Request
URL	Universal Resource Locator
UT	Universal Time
UTC	Universal Time Coordinate

V

VOS	Virtual Operating System
-----	--------------------------

W

WFC	Wide Field Camera
WG	Working Group
WWW	World Wide Web (CERN distributed hypermedia information retrieval system)

X

XAS X-ray astronomy Analysis System

Y**Z**

Addendum to the SAX Observer Handbook

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15 September 1997

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1. Introduction

BeppoSAX was successfully launched from Cape Canaveral on April 30, 1996. After launch, all satellite sub-systems have been checked-out (Commissioning phase); the first calibration phase (Science Verification Phase, SVP) has been carried out in the period July - September 1996, after which the AO1 program started.

This **Addendum** to the **SAX Observers' Handbook** contains the most relevant updated information after in flight operations.

Scientific instruments and system components performed nominally (or better) with the following modifications :

- MECS unit 1 no more operative since May 1997.
- Due to sunlit contamination the LECS can be operated only in earth shadow : this introduce further constrains on the observing window in order to achieve observing efficiency typically 30% – 60% of that of MECS.
- Attitude system : due to a series of gyro failures, a new pointing mode - making use of 1 gyro only – (1 gyro mode) has been implemented and successfully uploaded on board on Aug., 1997. For the AO2 phase we expect to operate the satellite in gyro-less mode. This mode will rely primarily on the use of star trackers. Furthermore the typical manoeuvre will be typically 1-2 orbits, that will set the minimum pointing duration to 20 ksec.

2. Pointing constraints

As from Aug. 96 BeppoSAX is operated in 1-gyro mode with very good results. Given our history of gyro problems we expect that the AO2 program, starting on Mar.1, 1998 will be followed through in gyro-less mode.

In gyroless mode, which is currently under development, slewing to source and the maintenance of the pointing will depend more heavily on the availability on stars in the field of view of the three orthogonally mounted star trackers than previously. We are developing slew and orientation strategies specifically taking this into account.

The major effect will be to reduce the time window durations within which a particular source can be observed, but should not reduce the probability that BeppoSAX can actually

point at that particular source - even though this last situation cannot be completely excluded.

Thus operating in gyroless mode should not be a problem for the normal time unconstrained observations, but will effect the time constrained and Target of Opportunity significantly.

It is unfortunately not possible to verify proposals for observation planning constraints in gyroless mode prior to their approval

3. LECS

No relevant changes in the first version of the LECS handbook are needed. The following figures updates the corresponding figures in the SOH.

Fig. 1 shows the overall on axis (default pointing mode) effective area of the LECS. Fig. 2 gives the 5σ minimum detectable count rate in the bands 0.1-10 keV and 0.1-1 keV. Figs. 3-8 give the power law, optically thin plasma emission (Mewe-Kaastra model) and black body conversion factors in the 0.1-10 and 0.1-1 keV bands, as a function of the power law index, gas temperature and absorbing column along the line of sight. Figs. 9 and 10 give the LECS sensitivity in detecting the oxygen 0.57 and iron 6.7 emission lines for two typical exposures: 10 and 100 ks.

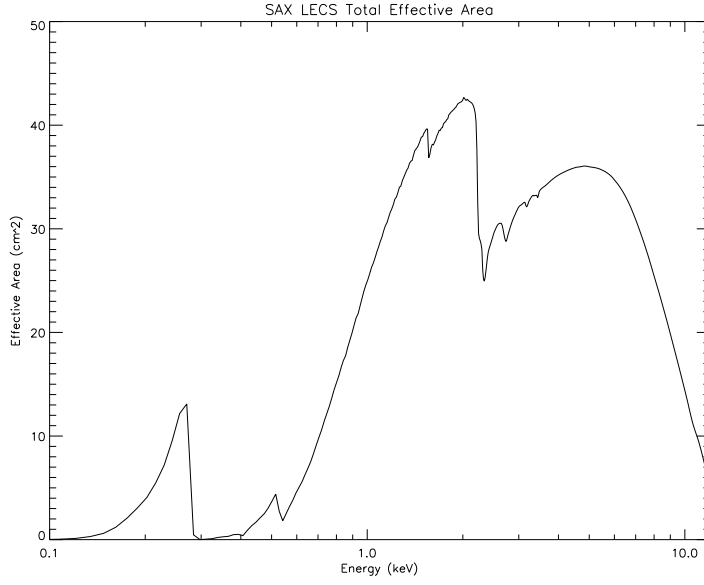


Fig. 1.— The overall on axis effective area of the LECS

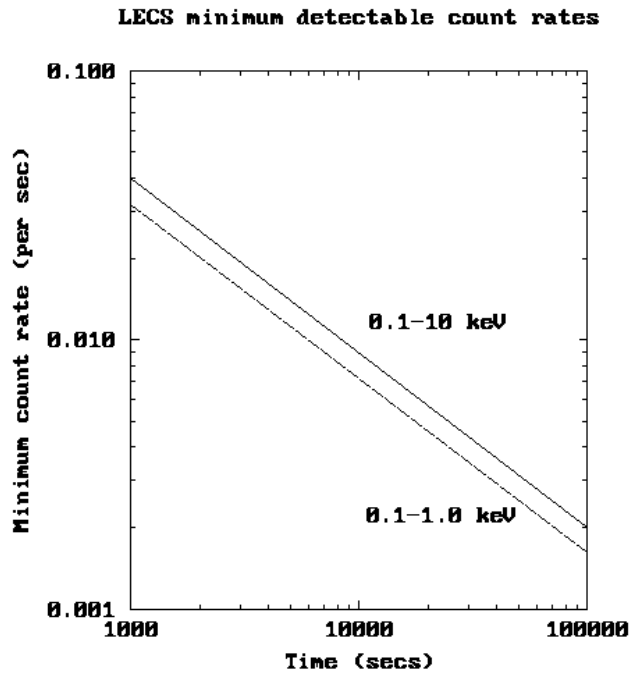


Fig. 2.— LECS 5σ minimum detectable source count rates

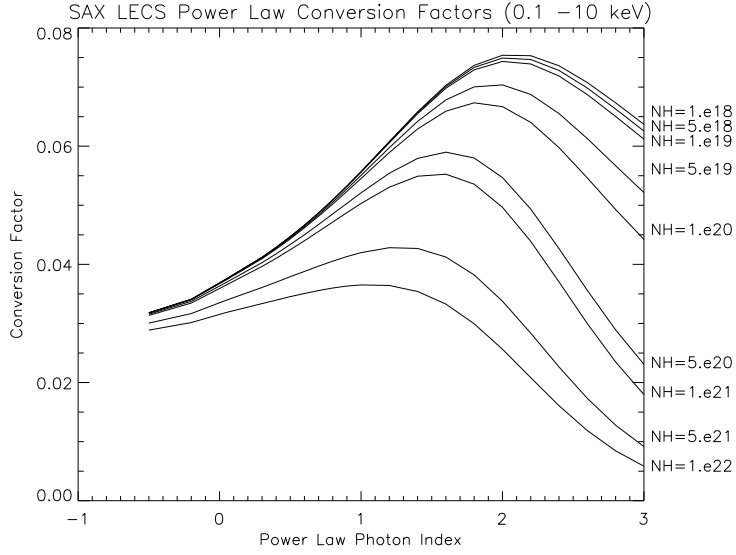


Fig. 3.— LECS 0.1-10 keV power-law conversion factors

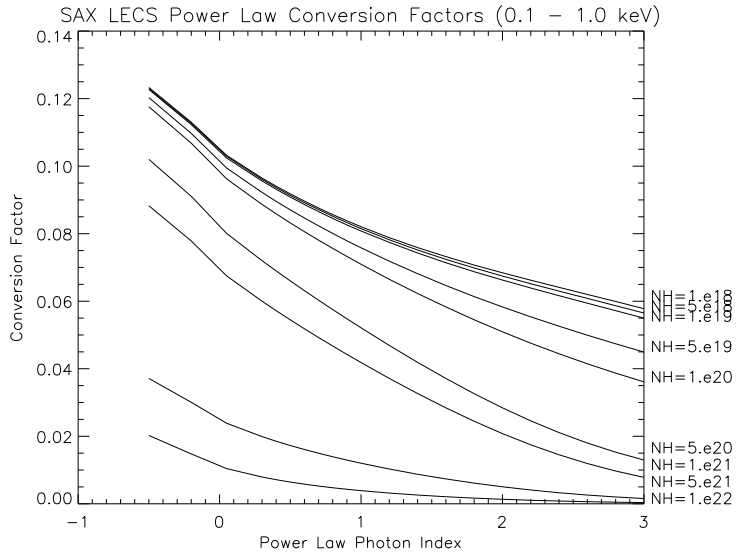


Fig. 4.— LECS 0.1-1 keV power-law conversion factors

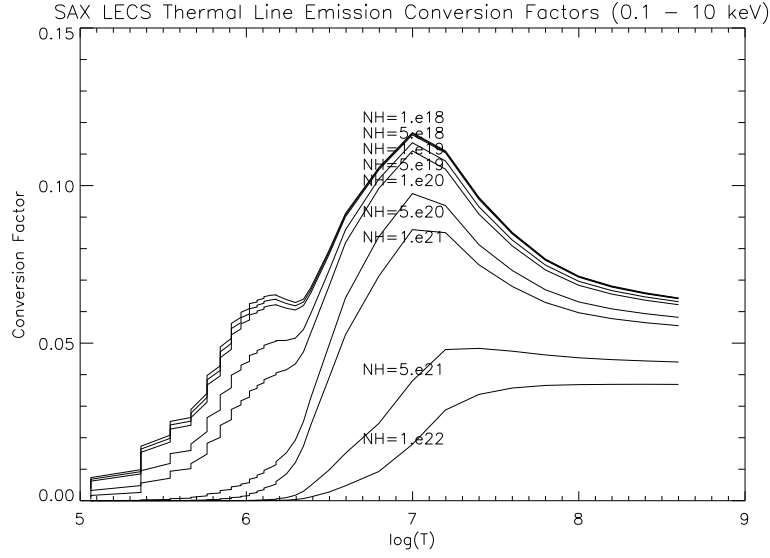


Fig. 5.— LECS thermal spectrum 0.1-10 keV conversion factors

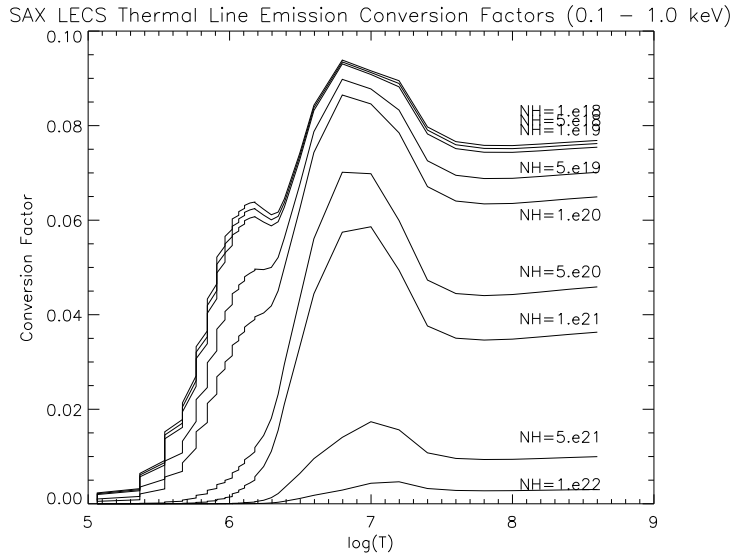


Fig. 6.— LECS thermal spectrum 0.1-1 keV conversion factors

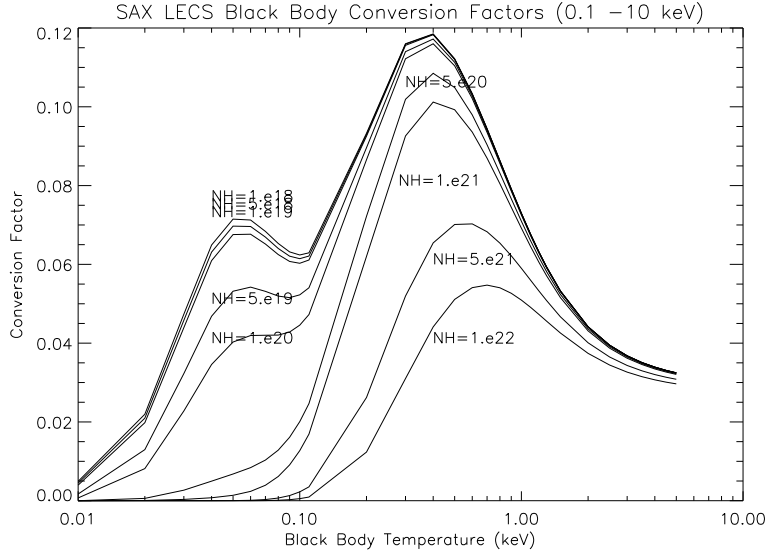


Fig. 7.— LECS black body 0.1-10 keV conversion factors

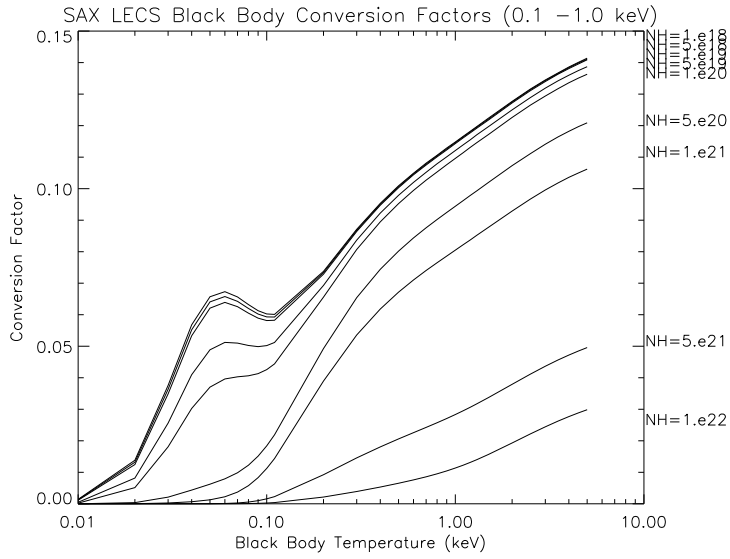


Fig. 8.— LECS black body 0.1-1 keV conversion factors

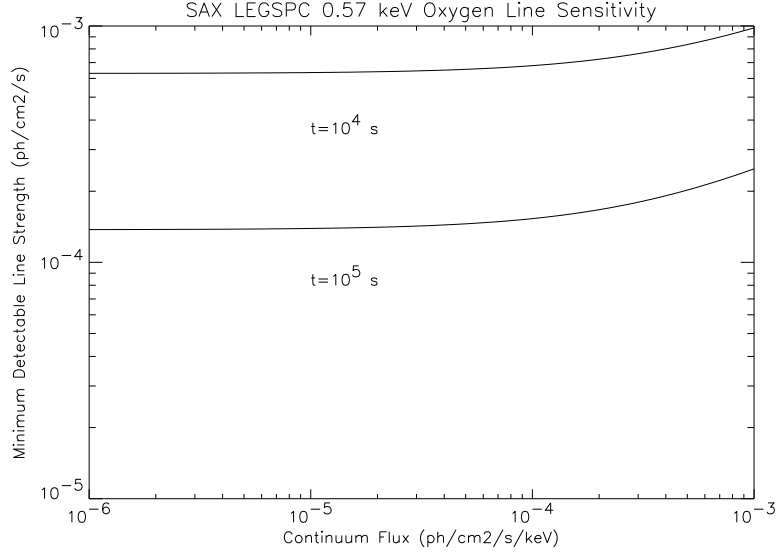


Fig. 9.— LECS 0.57 keV oxygen line sensitivity

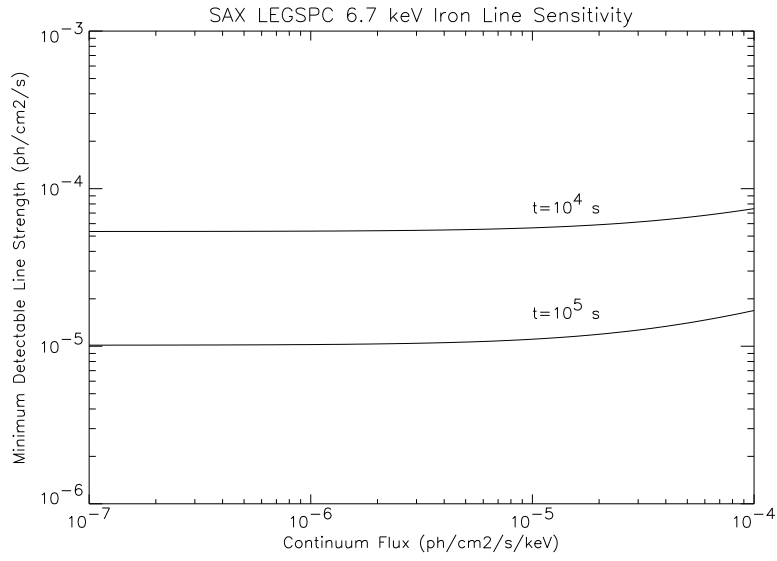


Fig. 10.— LECS 6.7 keV iron line sensitivity

4. MECS

The Medium Energy Concentrator Spectrometer (MECS), as described in Section 4.4 of BeppoSAX Handbook, consists of three identical units. On May 6 1997 unit 1 (M1) developed a fault due to the gas cell high voltage (HV) supply. Since then, scientific operations of the instruments have been carried on with two units (M2 and M3).

4.1. Performance

The MECS overall characteristics are reported in Tables 1 and 2 of the section 4.4 of the Handbook. In Table 1, however, the on-axis effective areas are reduced to the following values:

Effective on axis collecting area (2 units)

1.5 keV 25 cm²

6.4 keV 96 cm²

8.1 keV 69 cm²

4.2. Effective Area

The effective area of each unit has been tested during the Science Verification Phase using several observed sources. An "ad hoc" correction was applied to the mirror effective area to better model the gold reflectivity at the 2 keV edge. The total effective area for the present instrument configuration is shown in Fig. 11 as function of energy for different off-axis angles.

4.3. Energy resolution and linearity

Energy resolution as measured during the on-ground calibration is reported in paragraph 4.4.2.2 of the Handbook.

The in-flight energy-channel relation, that presents a jump at the Xenon L edge, has been evaluated from some SVP sources (the photomultiplier HVs are different from the on-ground calibration values). The jump, determined fitting the bump in the Crab spectrum, is 73.7 eV. The non-linear energy-channel relation is taken into account in the instrument response matrix.

4.4. Background

The MECS background can be considered as sum of two main components: the instrumental and the diffuse one. Work about the modeling of the MECS background is in progress using the entire SVP dataset. The goal of this work will be to supply a model as a function of energy and position in the field of view.

The instrumental background is measured during observations of the dark Earth, and consists of two components:

- a spatially uniform component made of two almost flat plateaus connected by a step between 4.5 and 5 keV
- a residual Fe line feature which varies with the inverse of the distance from both calibration sources. This component is not negligible in the centre. The intensity scales with the sum of the intensities of the calibration sources, and therefore the importance of this component will diminish as the Fe-55 sources will decay.

The other observed component, the cosmic diffuse background, is of course vignettted by the optics.

Spectra of the instrumental and total background for each unit collected over an equivalent area of 0.22 cm^2 are shown in Fig. 12. They represent the average spectrum over the whole Berillium window. The total (diffuse + instrumental) background has been determined from some 370 ks of dark Earth pointing and 1.1 Ms of blank field pointing obtained during the SVP phase. In the central part of the detector (9' radius), the average count rate of the total residual background is $4 \times 10^{-3} \text{ cts s}^{-1} \text{ cm}^{-2} \text{ keV}^{-1}$ ($1 \times 10^{-4} \text{ cts s}^{-1} \text{ arcmin}^{-2}$) where the instrumental contribution is $2 \times 10^{-3} \text{ cts s}^{-1} \text{ cm}^{-2} \text{ keV}^{-1}$ ($5 \times 10^{-5} \text{ cts s}^{-1} \text{ arcmin}^{-2}$).

4.5. Instrument sensitivity

4.5.1. Minimum detectable count rate

Fig. 13 shows the minimum observation time required for a significant detection. The criterium used is 5σ over the background for background limited observations and 10 photons for photon limited observations. The signal is collected in a spot of 4' (2.15 mm) that contains almost 87% of the signal. The background count rate considers both particle and diffuse components.

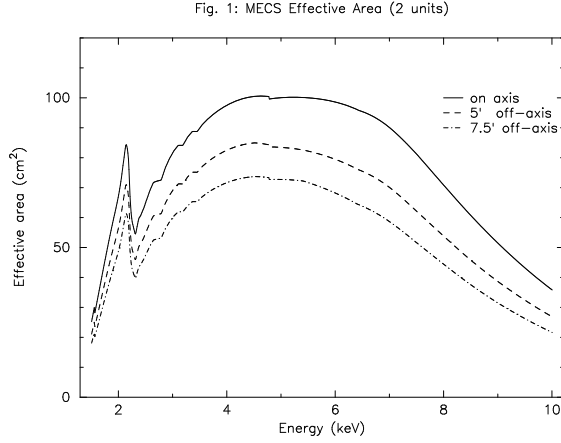


Fig. 11.— The overall on axis, 5 and 7.5 arcmin offaxis effective area of the MECS (two units).

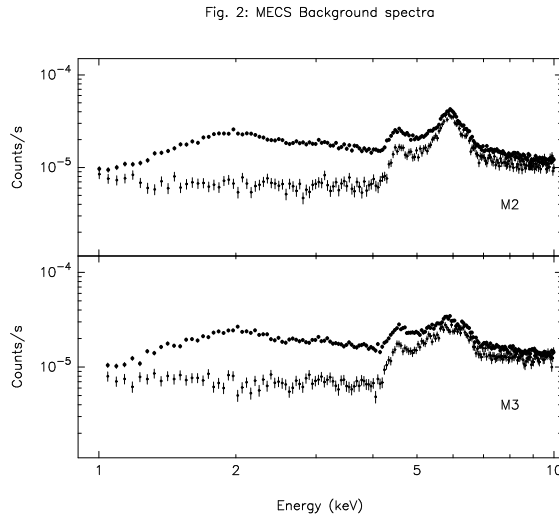


Fig. 12.— MECS2 and MECS3 background spectra integrated over an equivalent area of 0.22 cm^2 . The small dots represent the instrumental component; the big dots are relative to the total (diffuse + instrumental) background.

4.5.2. *Minimum detectable Fe line strength*

Fig. 14 shows the sensitivity to the 6.4 keV Fe line for observation time of 10^4 and 10^5 s. The criterium used is 5σ over the background continuum for background limited observations and 10 photons for photon limited observations. The considered energy detection element is the FWHM and the detection spot is 4'.

4.5.3. *Count rate estimation*

Due to the failure of M1, the total effective area is reduced of about 30%. Figures 4.4.5, 4.4.6 and 4.4.7 of the Handbook, that show the energy to count conversion factor, have to be reduced by the same amount in order to estimate the actual count rate.

4.6. **Data collecting modes supported for observer**

Paragraph 4.4.4 of the Handbook contains all information about the MECS operational supported modes.

5. **HPGSPC**

The configuration of the High Pressure Gas Scintillation Proportional Counter (HPGSPC) as described in Section 4.5 of issue 1.0 of BeppoSAX Observers' Handbook was not essentially changed during in-flight operation. Moreover, the in-orbit measured background turned out to be very similar to the pre-launch estimated value reported in the Handbook. This means that the sensitivity of the instrument is essentially unchanged as a result of in-flight operation.

A typical sequence of operations in orbit is shown in Fig. 15, where two consecutive orbits of the HPGSPC are reported while BeppoSAX was pointing the Low mass X-ray binary Her X-1.

During the South Atlantic Anomaly passage the high voltages of the Photomultipliers are turned to zero in order to avoid a very high level of the background count rate which could damage the PMTs. Following the SAA passage the high voltages of the Gas Cell and of the PMTs are turned on to the nominal values and the Active Gain Control System is activated in order to equalise the gain of all the seven PMTs.

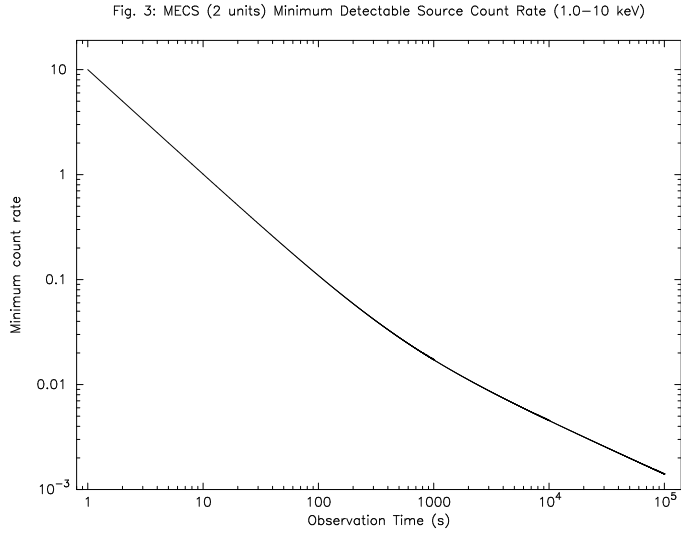


Fig. 13.— MECS (two units) 5σ minimum detectable source count rates

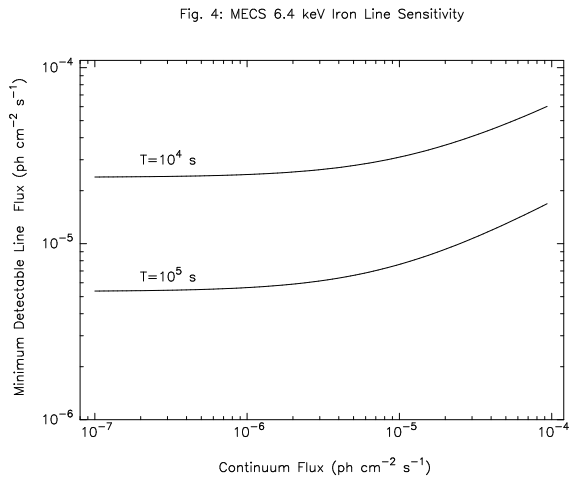


Fig. 14.— MECS (two units) 6.4 keV iron line sensitivity

5.1. Performance

The HPGSPC overall characteristics are reported in Table 1 of Section 4.5 of the Handbook. The Voltage applied to the Scintillation Region has been reduced to 10 Kv. Also, the starting nominal values of the seven photomultipliers were increased twice during the mission so to balance the gain loss due to the aging of PMTs.

5.2. Collimator

Four collimated X-ray sources, a mixture of Fe^{55} and Cd^{109} radioactive sources which emits lines at 5.9, 22.2, 24.9 and 88 keV, are nested in the collimator and depending on collimator position (ON/OFF axis) illuminate different areas of the detector. As will be discussed in the Background section this has an impact on background reduction and subtraction strategy.

5.3. Collimator configuration modes

In order, to optimise the background subtraction strategy, it is suggested to use as a standard law the "One Sided Cycle", in which the background flux is monitored on only one side at -3° degrees (OFF-). Standard stay time is 96 sec.

5.4. Effective Area

The effective area of HPGSPC has been calculated during the Science Verification Phase using several observed sources. The total effective area after the in-orbit calibration and for the present instrument configuration is shown in Fig. 16.

5.5. Energy linearity and resolution

The channel to energy relation during in-flight operation has been verified to be linear using both lines due to calibration sources and lines due to impurities in the beryllium window. Results on linearity are shown in Fig. 17 where the best fit to all lines is reported.

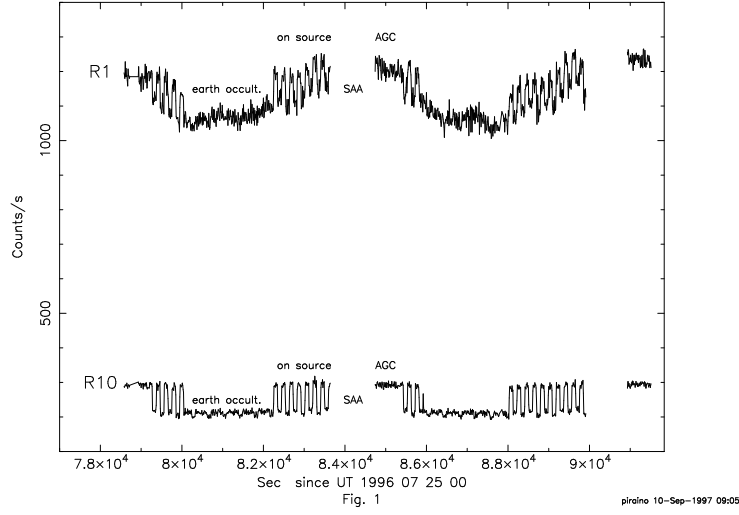


Fig. 15.— Typical orbit operation of the HPGSPC. Data refers to the SVP observation of Her X-1.

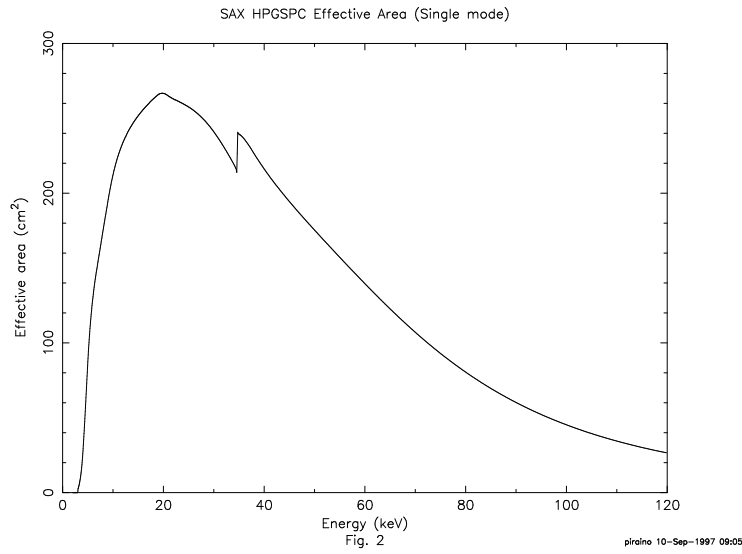


Fig. 16.— HPGSPC effective area (Single Mode) after in-flight calibration.

The energy to channel relationship for the actual in-flight configuration is currently given by

$$E = -0.0761 + 0.0311 * PHA \quad (1)$$

when the detector is operated in SE mode. Energy resolution as a function of the energy was also measured during in-flight operation using calibration lines. The energy resolution of HPGSPC is of about 10.5% at 6 keV and 2.8% at 60 keV. The curve, shown in Fig. 18, has been fitted with the following function:

$$\frac{\Delta E}{E} = 2.83 \left(\frac{E}{60 \text{ keV}} \right)^{-0.56} \quad (2)$$

This is in agreement with what we measured during on-ground calibration, showing that effects of temperature gradients within the detector and mechanical stresses caused by g-zero environment are negligible.

5.6. Background

Characterization of the background has been one of the most important goal of the Science Verification Phase. The residual instrumental background (in the 4 – 100 keV band) after on-board reduction is about $2.015 \times 10^{-3} \text{ cts s}^{-1} \text{ cm}^{-2} \text{ keV}^{-1}$ which is in very good agreement with the value reported in the 1.0 issue of the handbook.

Unfortunately the in-flight background, see Fig. 19, is highly structured, showing several lines due to residual events from calibration sources and to impurities in the beryllium window. Moreover, background sampled with the collimator in the ON position is different from the background observed by the HPGSPC when collimator is in the OFF positions. In order to properly subtract the background an "ON/OFF difference" spectrum has been accumulated with very high statistics during a long exposure on blank fields (170 ksec.).

In Fluorescence Gated Mode the background is reduced of about a factor of fifty. However, also the signal is strongly reduced because the electronic efficiency in detecting double events is lower than expected. Preliminary results show that in SE and FG mode the same signal to noise ratio can be obtained. Calibration of FG mode is currently running.

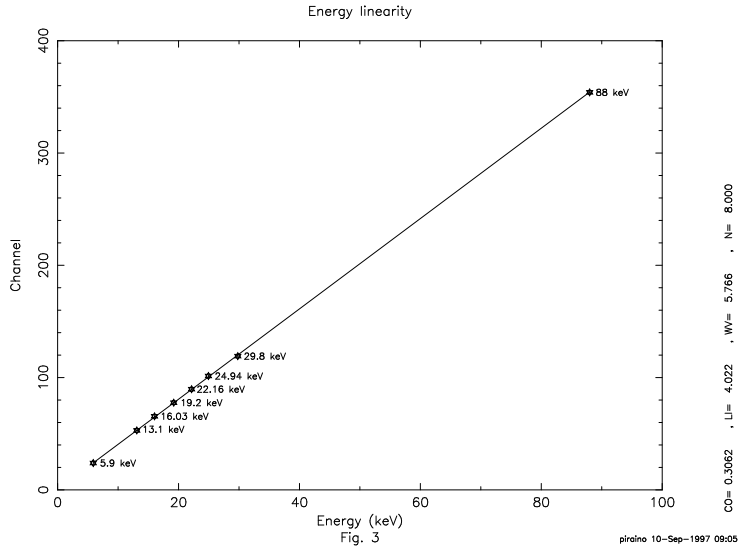


Fig. 17.— Channel to energy relation measured using lines due to calibration sources and lines due to impurities in the beryllium window.

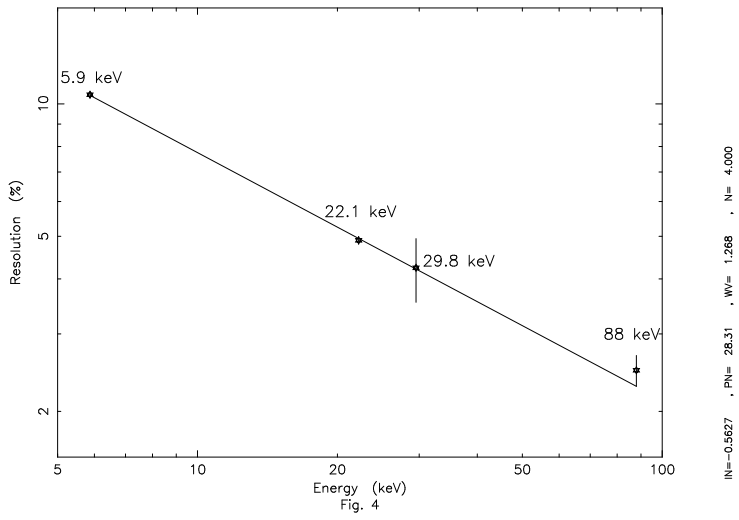


Fig. 18.— Energy resolution versus energy.

5.7. Instrument sensitivity

5.7.1. Minimum detectable count rate

In Fig. 20 the minimum detectable source count rate is reported as a function of observation time in the 4–60 keV band (in SE mode) and in the 34–100 keV band in FG mode. The measured in-flight background values are taken into account.

5.7.2. Expected Count Rates

In Fig. 20–25 we show the HPGSPC Conversion Factor in three different energy ranges (4–34, 34–120, 4–120 keV) recalculated with the actual in-flight configuration. Power Law and Thermal Bremsstrahlung are used as incident spectrum.

5.7.3. Minimum detectable Fe line strength

Fig. 26 shows the sensitivity of the HPGSPC to the 6.4 keV Fe line for an observation time of 10^5 s. The criterion used is 5σ over the background continuum. In the same figure is also reported the minimum detectable strength for an emission cyclotron line centred at 51 keV with a width of 15 keV (FWHM) and for an observation time of 10^5 s.

5.8. Data collecting modes supported for observer

Paragraph 4.5.5 of the BeppoSAX handbook contains all information about the HPGSPC supported operational modes.

6. PDS

No relevant changes in the first version of the PDS handbook are needed. Making reference to the subsections of the SAX Handbook, issue 1.0, we point out the following.

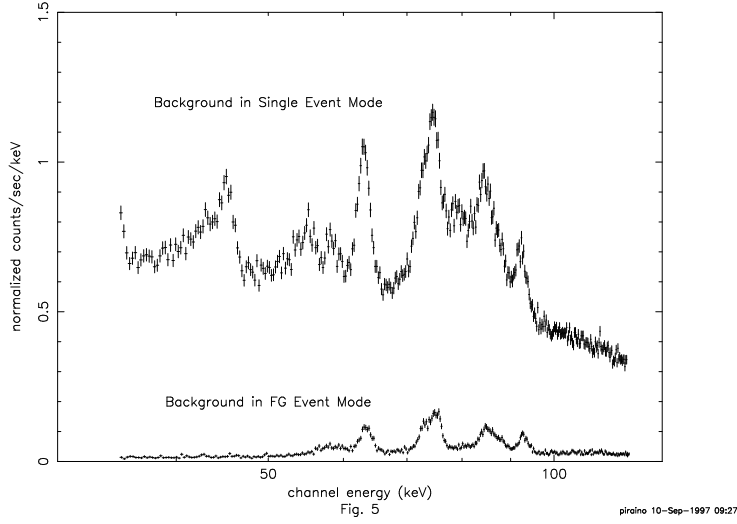


Fig. 19.— The instrumental background spectra in Single Event and Fluorescence Gated mode.

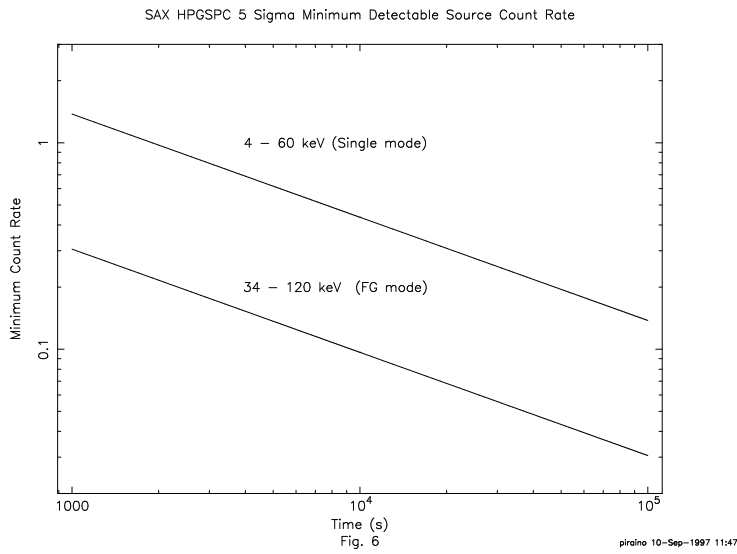


Fig. 20.— HPGSPC 5σ minimum detectable source count rate

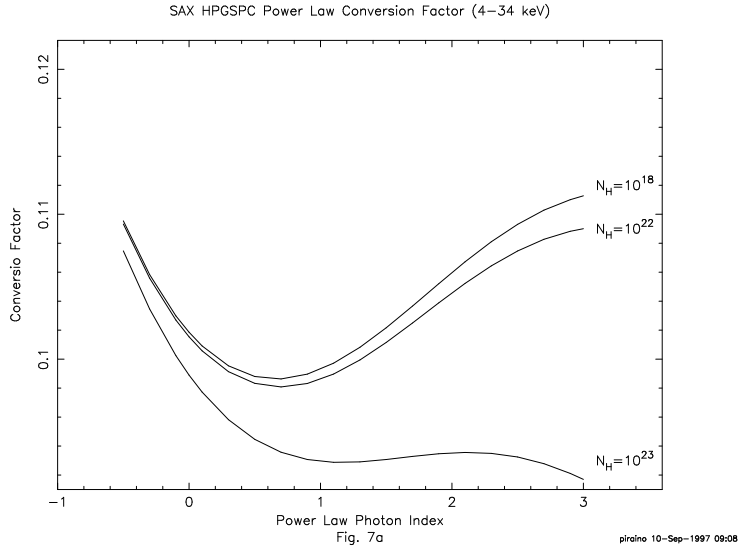


Fig. 21.— HPGSPC Power Law Conversion Factor (4-34 keV).

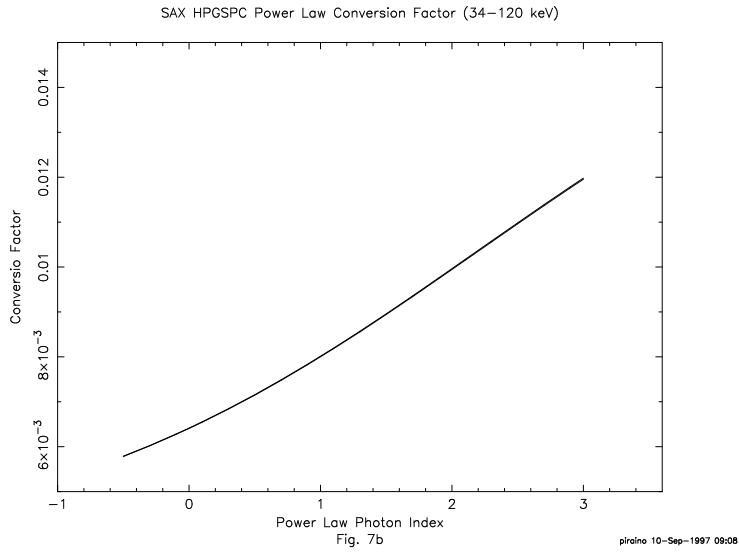


Fig. 22.— HPGSPC Power Law Conversion Factor (34-120 keV).

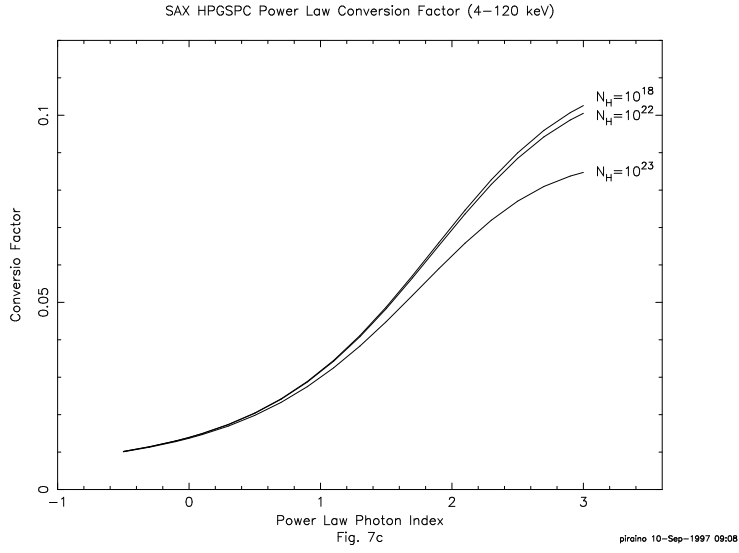


Fig. 23.— HPGSPC Power Law Conversion Factor (4-120 keV).

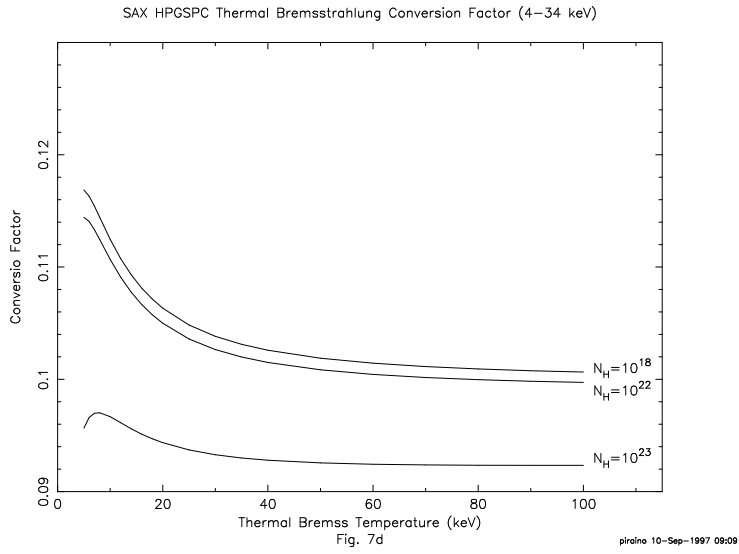


Fig. 24.— HPGSPC Thermal Bremsstrahlung Conversion Factor (4-34 keV).

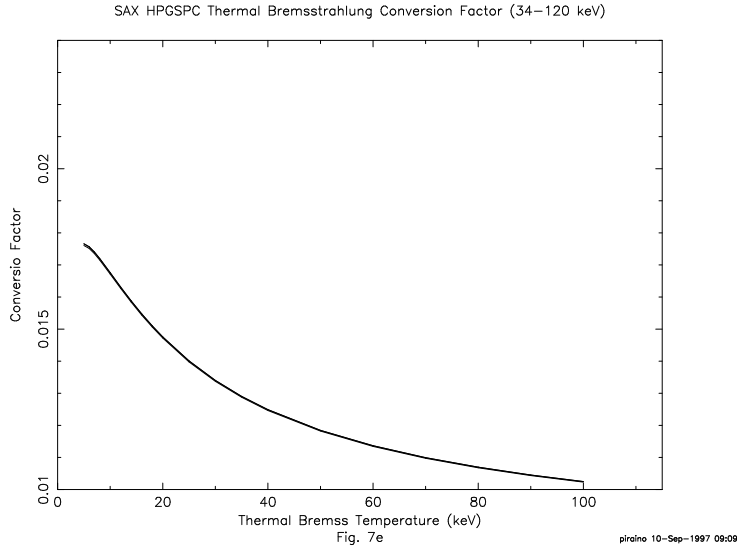


Fig. 25.— HPGSPC Thermal Bremsstrahlung Conversion Factor (34-120 keV).

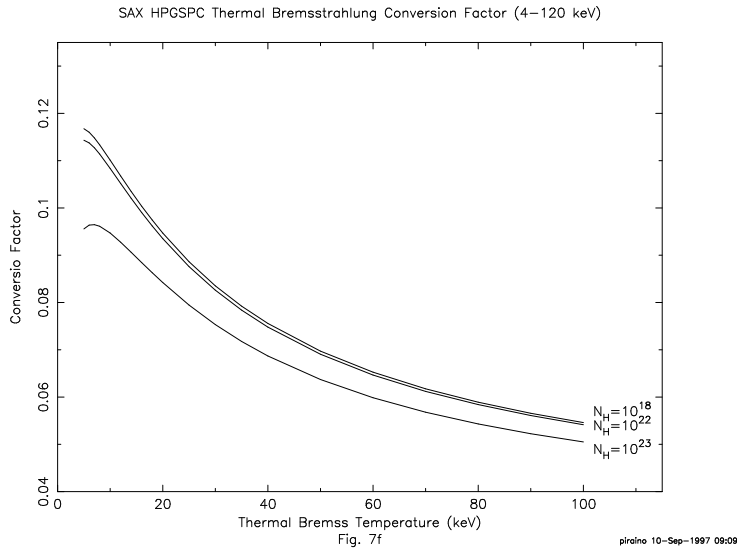


Fig. 26.— HPGSPC Thermal Bremsstrahlung Conversion Factor (4-120 keV).

6.1. Movable Calibration System (MCS)

SOH section 4.6.1.4.2.

We notice that the radioactive source used is Co57 (lines at 14.4 keV, 122.06 keV and 136.5 keV, with a relative intensity of 8.4%, 85% and 11%, respectively).

6.2. Gamma-Ray Burst Monitor (GRBM)

SOH section 4.6.1.5

The expected 5 sigma sensitivity of GRBM in 40-700 keV energy band is about 10^{-7} erg cm² s⁻¹ for the two detectors that have their axis parallel to the WFCs. Data analysis of the GRBM is in charge of a dedicated working group. For further details on GRBM contact F. Frontera (e-mail in sect. 7).

6.3. Energy resolution

SOH section 4.6.3.2

The dependence of energy resolution on energy is better fitted with a broken power law. The correct dependence is described in the S/W package distributed by SAX/SDC. For further details, refer to the paper by Frontera et al., A&AS, 122, 357 (1997).

6.4. Background

SOH section 4.6.3.3

With fixed thresholds of the PSA (channels 3 - 150), the overall measured background level in the 15-300 keV energy band is similar to that reported in the SAX handbook issue 1.0, that was based on pre-flight estimates. Fig. 27 shows a typical in-flight background spectrum (4 units). This spectrum can be roughly described by a power law ($KE^{-\alpha}$) with $K=7.6 \times 10^{-3}$ and $\alpha = 0.84$.

The background spectrum is slightly different from the pre-flight estimates. We have updated in Figs. 28, 29 and 30, SOH Fig. 4.8 (5σ sensitivity of the instrument in three energy bands), Fig. 4.11 (time to detect a 5σ fractional variation in the X-ray flux of

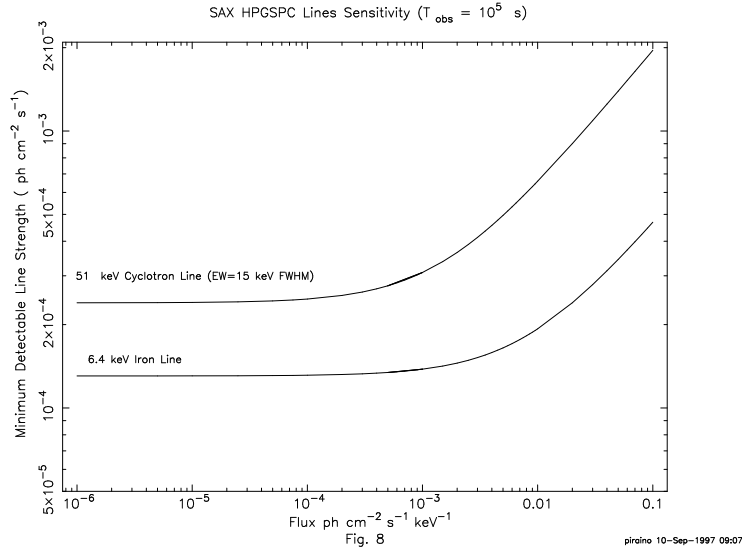


Fig. 27.— Lines sensitivity for an observation time of 10^5 s.

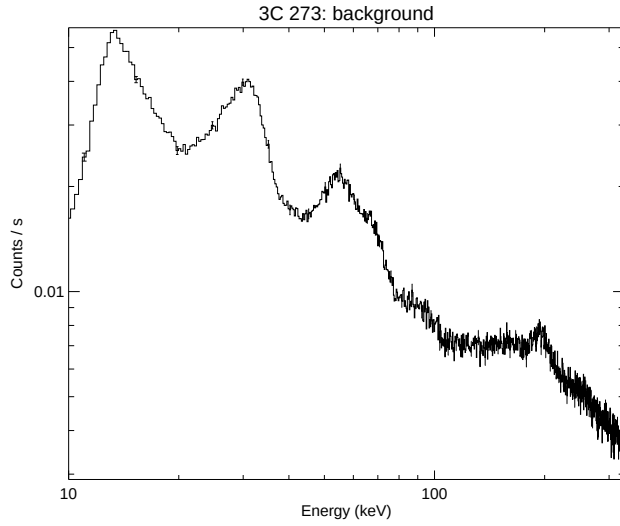


Fig. 28.— PDS background

Cygnus X-1 in three different energy bands), Fig. 4.12 (time to detect a 5 sigma fractional variation in the X-ray flux of NGC4151 in three energy bands) and Fig. 4.13 (5σ sensitivity of PDS to detect an emission line as a function of energy).

With variable rise time thresholds as a function of photon energy, the above background level can be lowered by a factor of about 1.6, with a appreciable change in the sensitivity figures. With this rise time selection the background level is on the average 80% times that quoted in the PDS handbook issue 1.0. We are currently working on this item to include some background selection criterion in the PDS specific S/W package.

6.5. Temporal modes

SOH section 4.6.5.2.2

Please correct a mistake concerning the code that indicates if data are transmitted separated by units or not as follows: a) if the data are transmitted separated by units: (_1); b) if the data are summed on pairs: (_2); c) if the data are summed on all units: (_4).

7. WFC

The in-flight performance of the WFC instrument during the first year of operations did not reveal any big surprises. It is as expected pre-flight and described in the handbook. A few additional remarks are appropriate.

7.1. Background

Pre-flight determined background levels were extrapolated from other experiments and subject to some systematic errors. Therefore, the levels were verified with an empty field observation at high galactic latitudes. The diffuse cosmic X-ray background was found to be $102 \pm 2 \text{ c s}^{-1}$ for both WFCs in the whole bandpass for the whole FOV. Detector background levels are time dependent, the lowest measured values are at about 40 c s^{-1} . The total background level then is nominally 140 c s^{-1} which is 10 c s^{-1} larger than specified in the handbook.

7.2. Sensitivity

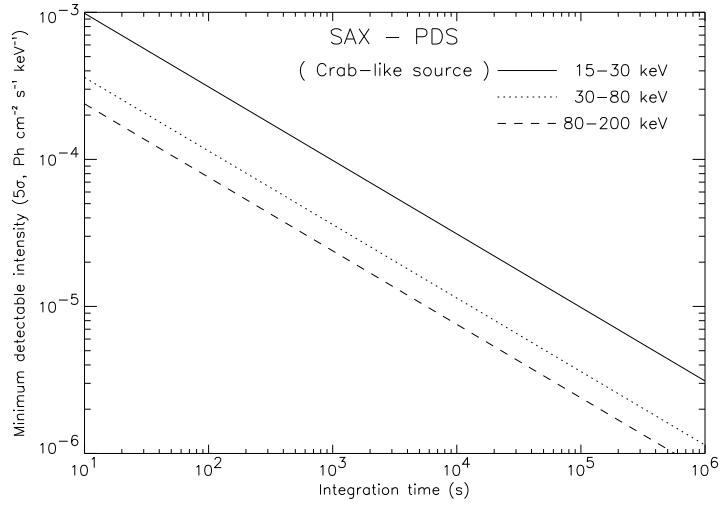


Fig. 29.— PDS 5σ sensitivity in three energy bands

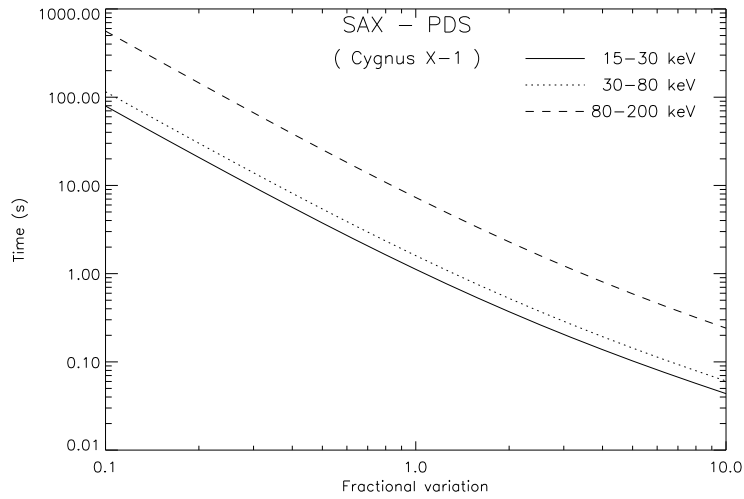


Fig. 30.— Time to detect a 5σ fractional variation in the X-ray flux of Cygnus X-1 in three energy bands.

A limited in-flight verification has been performed. Eight observations have been selected in which only weak sources are detected (i.e., the detected sources do not significantly contribute to the Poisson noise at other FOV locations) and which are pointed far from the galactic plane. Table 1 presents results for detected sources in these observations that are near the edge of detection and, therefore, represent a good probe of the detection limit. The quoted detection limits have been derived from the source detections by scaling the intensity to the center of the field of view and to a 5σ level. These results take notice of the newest understanding of the point spread function and confirm Fig. 4.7.2 for high galactic latitudes within a few tens of percents.

Detection limits are more difficult to predict for regions relatively close to the galactic plane. They are very dependent on the precise source configuration and intensities. Therefore, we emphasize that Figure 4.7.2 for near the galactic center only presents an indication of the detection limit. In particular circumstances it may be worse by a factor of 3.

7.3. Position accuracies

Position accuracies comprise of a statistical and a systematic component. The statistical component is readily determined by fitting the point spread function. The systematic component is due to instrumental and numerical effects which are not modeled in the point spread function. An analysis of this involved the positions of hundreds of point source detections with only minor statistical uncertainties. The distribution of the deviations between the measured sky positions and those expected from the catalog for a WFC with ideal imaging properties is Gaussian. The maximum deviation was found to be 3 arcmin. The distribution appears to be identical for both cameras and independent of position in the FOV. Therefore, one should always note that there is a systematic position uncertainty of about 3 arcmin radius. This probably does not take into account potential errors in the attitude solution of the satellite.

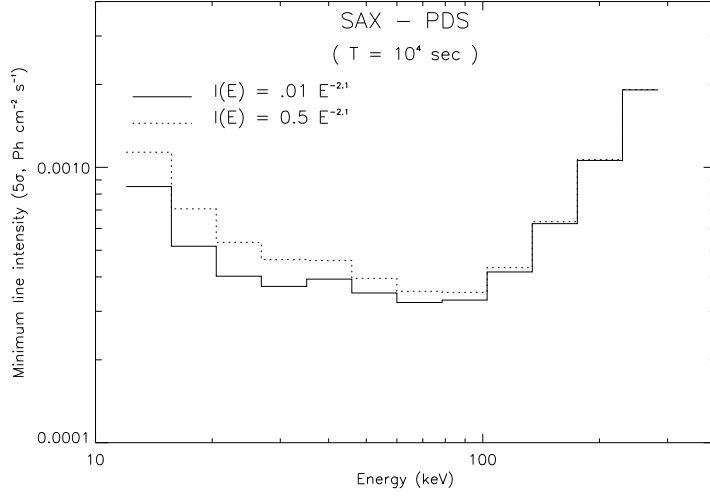


Fig. 31.— PDS 5 σ sensitivity for line emission a function of energy.

Table 1: Verification of detection limits in 2 to 8 keV

Exposure time (10 ³ s)	Source name	Intensity (mCrab)	Sigma	Detection limit (mCrab)
4.0	NGC 1275	16.8	8.1	4.7
5.5	Tycho SNR	8.4	9.0	3.2
	γ Cas	6.0	5.2	3.0
	X 0114+650	8.1	7.0	3.1
16	EXO 0748-676	6.6	7.5	2.3
17	ACO 2319	3.5	5.8	1.8
32	4U 1210-64	2.5	6.6	1.7
	η Car	4.4	8.1	1.5
36	AM Her	2.7	7.6	1.5
38	X 0142+614	3.1	7.8	1.1
74	AM Her	1.5	6.7	0.9